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Flowfield Measurements in a Separated and Reattached Flat Plate Turbulent Boundary Layer

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NOMENCLATURE

B	Bias
C_f	Skin friction coefficient, $2 U_\tau^2 / U_{ref}^2$
C'_f	Local skin friction coefficient, $2 U_\tau^2 / U_e^2$ or eq. (5-34) in backflow boundary layer
C_p	Pressure coefficient, eq. (4-2)
d_f	Fringe spacing
d_m	Minor axis of measurement ellipsoid (i.e., diameter of LV probe volume)
f	Frequency
H	Boundary layer shape factor, δ^* / θ
h	Boundary layer shape parameter, $(H-1)/H$; Height of backward-facing step; maximum thickness of separation bubble
k	Turbulence kinetic energy per unit mass, eqs. (4-4) and (4-5)
l_m	Major axis of measurement ellipsoid
M	Distance from wall to peak in transverse turbulence profile (current study); distance from wall to peak in axial turbulence profile (Simpson et al. data, ref. 1)
N	Distance from wall to location of maximum backflow velocity
n	Coordinate normal to streamwise direction
P	Total pressure
p	Static pressure
Q	Dynamic head pressure
$\sqrt{q^2}$	RMS streamwise turbulence component

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NOMENCLATURE (Cont'd)

R	Non-dimensional pressure gradient strength, $\delta/U_e(\partial U_e/\partial x)$
$Re_{x'}$	Reynolds number in backflow boundary layer, $U_N x'/\nu$
Re_{δ^*}	Reynolds number based on displacement thickness, $U\delta^*/\nu$
Re_θ	Reynolds number based on momentum thickness, $U\theta/\nu$
S	Precision index
s	Coordinate in streamwise direction
T	Static temperature
t	Time
t_{95}	95th percentile point for Student's "t" distribution
U	Mean velocity in axial, x-direction; Measurement uncertainty
U_{eff}	Mean effective cooling velocity of hot-film probe
U_i	Axial velocity component of inviscid flowfield
U_N	Maximum backflow velocity
U_τ	Friction velocity, $\sqrt{\tau_w/\rho}$
U^+	Non-dimensional axial velocity component, U/U_τ
u	Fluctuating velocity component in axial, x-direction
u_{eff}	RMS fluctuation of effective cooling velocity of hot-film probe
\overline{uv}	Reynolds shear stress
$\sqrt{u^2}$	RMS axial turbulence component
V	Mean velocity in transverse, y-direction

NOMENCLATURE (Cont'd)

V_B	Non-dimensional wake amplitude, eq. (5-23)
V_T	Non-dimensional shear velocity, eq. (5-24)
v	Fluctuating velocity component in transverse, y-direction
$\sqrt{v^2}$	RMS transverse turbulence component
W	Mean velocity in spanwise, z-direction
w	Fluctuating velocity component in spanwise, z-direction; universal wake function, eq. (5-13)
$\sqrt{w^2}$	RMS spanwise turbulence component
x	Axial coordinate relative to test section inlet
x_R	Axial location of reattachment
$x_{\delta^*_{\max}}$	Axial location of maximum separation bubble thickness
x'	Axial distance from reattachment location, $x_R - x$
x^*	Non-dimensional axial distance from reattachment, eq. (5-38)
y	Transverse coordinate relative to test surface
y^+	Non-dimensional transverse coordinate, yU_τ/ν
z	Spanwise coordinate relative to wind tunnel centerline
α	Test section divergence angle; angle of rotation of LV optics
$\overline{\alpha\beta}$	Streamwise turbulent shear stress component, eq. (5-39)
β	Clauser equilibrium parameter, eq. (5-15)
γ_{P_U}	Forward flow fraction (i.e., fraction of time flow moves in downstream direction)

NOMENCLATURE (Cont'd)

$\gamma_{P_{U_{\min}}}$	Minimum value of γ_{P_U} in profile near wall
γ_{P_V}	Transverse flow fraction (i.e., fraction of time flow moves away from test surface)
δ	Boundary layer thickness (i.e., location at which measured total pressure equals 99 percent of freestream total pressure).
δ_{99}	Boundary layer thickness (i.e., location at which $U = 0.99 U_e$)
δ_{995}	Boundary layer thickness (i.e., location at which $U = 0.995 U_e$)
δ^*	Displacement thickness
δ_1^*	Classical displacement thickness, $\int_0^\delta (1 - \frac{U}{U_{iw}}) dy$
δ_2^*	True displacement thickness, $\int_0^\delta (1 - \frac{U}{U_{iw}}) dy - \int_0^\delta (1 - \frac{U_i}{U_{iw}}) dy$
δ_3^*	Pressure-based displacement thickness, $\int_0^\delta (1 - \frac{U}{U_i}) dy$
θ	Momentum thickness
θ_1	Classical momentum thickness, $\int_0^\delta \frac{U}{U_{iw}} (1 - \frac{U}{U_{iw}}) dy$
θ_2	True momentum thickness, $\int_0^\delta \frac{U}{U_{iw}} (1 - \frac{U}{U_{iw}}) dy - \int_0^\delta \frac{U_i}{U_{iw}} (1 - \frac{U_i}{U_{iw}}) dy$
θ_3	Pressure-based momentum thickness, $\int_0^\delta \frac{U}{U_i} (1 - \frac{U}{U_i}) dy$
κ	Half-angle between intersecting laser beams; experimentally determined constant in eq. (5-13)
Λ	Boundary layer shape parameter, δ^*/δ ; Pohlhausen pressure-gradient parameter, eq. (5-36)
μ	Viscosity

NOMENCLATURE (Cont'd)

ν	Kinematic viscosity
ξ	LV inclination angle in y-z plane
Π	Boundary layer wake parameter
ρ	Density
τ_w	Shear stress at wall
ϕ	Angle of streamline relative to test surface
ψ	Stream function, eq. (5-2)
ω	Vorticity, $\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}$

Subscripts/Superscripts

-	Overbar, denotes time average except for LV measurements which are ensemble-averaged
~	Wavy overbar, denotes magnitude of instantaneous velocity
^	Caret overbar, denotes nondimensional parameter
e	Quantity measured at $y = \delta$
ref	Quantity measured at reference location
w	Quantity measured on test surface

FLOWFIELD MEASUREMENTS IN A SEPARATED AND REATTACHED FLAT PLATE TURBULENT BOUNDARY LAYER

William P. Patrick

SUMMARY

An experimental investigation of turbulent boundary layer separation with reattachment on a flat plate test surface was conducted in the United Technologies Research Center Boundary Layer Wind Tunnel. The objective of the study was to provide a comprehensive set of data for use in assessing the accuracy and assisting the further development of computational procedures for predicting boundary layer separation phenomena. The approach was to conduct a large scale, two-dimensional flow simulation of an airfoil turbulent separation bubble at low subsonic Mach number by imposing a strongly adverse and subsequent favorable pressure gradient. A combination of laser Doppler velocimetry, hot-wire anemometry, pneumatic probing techniques, and flow visualization were used as diagnostics.

The boundary layer separated and reattached over an axial distance of approximately 55 cm. The maximum bubble thickness, measured to the height of the mean dividing streamline, was 17 cm, which was twice the thickness of the inlet boundary layer. A strong backflow region in which the flow moved upstream 100 percent of the time was measured near the test surface over the central 35 percent of the axial extent of the bubble. A laminar backflow boundary layer having pseudo-turbulent characteristics including a log-linear velocity profile was generated under the highly turbulent backflow. Velocity profile shapes in the reversed flow region only matched Simpson's universal backflow profile at the upstream edge of the separation region where the backflow was intermittent. A smoke flow visualization movie and hot-film measurements revealed low frequency nonperiodic flapping at reattachment. However, forward flow fraction data at reattachment and mean velocity profiles in the redeveloping boundary layer downstream of reattachment correlated with backward-facing step data when the axial dimension was scaled by the distance from the maximum bubble thickness to reattachment.

Other principal observations concerning the separation bubble flowfield were that an outer inviscid rotational flow can be defined which essentially convects over the blockage associated with the inner, viscously dominated bubble recirculation region. In the outer flow region, velocity profiles were similar over the axial extent of the bubble while significant profile alteration occurred within the inner flow region, including the development of the reversed flow boundary layer at the base of the recirculation zone. The identification of this three-tiered structure is believed to have important implications relative to the numerical modeling of the flowfield.

CHAPTER 1

INTRODUCTION

Development of reliable numerical procedures for predicting compressor and turbine airfoil boundary layer separation is important to the gas turbine design process since the potential for occurrence of separation is high, when it occurs its effects are usually large, and present empirically based prediction methods have significant shortcomings.

The adverse pressure gradient responsible for boundary layer detachment can arise from local surface curvature effects or be imposed on the boundary layer by the outer flow (flow deceleration or incident shock waves). Depending on the strength of the adverse pressure gradient and the boundary layer characteristics (whether laminar or turbulent and the boundary layer shape factor) separation can occur on either the airfoil pressure or suction surface and at various axial positions. The boundary layer may remain detached or reattach after a short or long distance (as a percent of chord) and it may undergo transition to turbulence if initially laminar.

A schematic of a turbomachinery blade showing several of the possible separations in terms of location, source and downstream development is given in figure 1-1. A closed leading edge bubble (termed a transitional bubble) is shown on the suction surface where typically deceleration of a laminar boundary layer causes separation, and transition to turbulence in the bubble shear layer fosters reattachment. Under a sufficiently adverse pressure gradient imposed by the outer flow, reattachment may not occur and the phenomenon of massive stall will result. A second form of suction surface separation encountered in the outboard regions of supersonic fan blades is shown further aft. This shock-induced phenomenon usually involves separation of a turbulent boundary layer and arises from interaction of the boundary layer with a bow shock from a neighboring blade. Depending primarily on shock strength and the degree of downstream diffusion, reattachment may or may not occur. Another region of surface separation is the airfoil trailing edge where the thick, blunt geometries required for structural and durability reasons invariably result in a surface curvature-induced separation. A fourth separation phenomenon is shown on the pressure side where surface curvature can induce a turbulent boundary layer ("cove") separation which subsequently reattaches under the influence of a favorable pressure gradient. Complicating these isolated phenomena is the possibility of interaction where, for example, a boundary layer weakened by negotiating the pressure rise of a shock may separate upstream of the trailing edge under the influence of diffusion and hence alter the trailing edge separation.

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It is therefore clear that the potential for occurrence of separation is high and that once separated, the subsequent downstream development can have a significant impact on the aerodynamic performance (and for the turbine application, also the surface heat transfer). While the prediction of the inception of separation is important, and in some cases reasonably well treated by existing methods, the ability to predict the subsequent downstream flow development is equally important. Existing airfoil design procedures typically rely upon an inviscid transonic cascade calculation to predict the overall flowfield and a coupled boundary layer calculation to account for near surface viscous effects. In the absence of separation the procedures are generally satisfactory for design purposes. When separation occurs, however, lack of a reliable calculation method requires the use of approximate methods derived from test data and past experience. This empirical approach, while successful in many applications, not only limits the designer to interpolation within the experience base but also presents problems in the application of the available codes. For example, in treating either a closed leading edge or shock-induced separation bubble, it may be possible to use correlations to define the approximate extent of the separation region. Uncertainty exists, however, in boundary layer characteristics aft of the bubble. Since these are required to initiate an attached boundary layer calculation over the remainder of the airfoil surface, the accuracy of the overall airfoil calculation procedure is impacted.

The focus of the present study was the pressure side "cove" separation depicted in figure 1-1. The approach was to conduct a large-scale, two-dimensional flow, low Mach number simulation on a flat plate test surface. The flat plate geometry was selected since it provided the simplest test case for code assessment purposes. There have been no previous investigations of this turbulent separation bubble geometry using non-intrusive laser velocimetry although Simpson (refs. 1-4) has performed extensive research relative to flat plate turbulent boundary layer separation without downstream reattachment. Simpson's work has provided significant information regarding both the mean and turbulent velocity fields within the separated flow region and some of his results apply directly to the leading edge region of the bubble investigated in this study. Although a number of other investigators have conducted closed separation bubble studies which have indirect relevance to the problem considered here, test geometries invariably involved rapid surface curvature and salient edges which produced fixed separation points and also affected the development of the reversed flow region within the bubble. Only Perry and Fairlie (ref. 5) and Cutler and Johnston (ref. 6) have reported investigations of flowfields comparable to the current study. Their studies, described in Chapter 2, used pitot and hot-wire traverses to obtain data within the separation bubble and, in addition, Cutler and Johnston used thermal tufts at the wall.

For the near future, computer codes providing numerical solutions of the Reynolds-averaged equations will continue to be the most useful engineering approach for the solution of flowfields having turbulent separation bubbles (ref. 7). Such codes use numerical correlations and zonal modeling to divide the flowfield into several regions, each dominated by a particular type of flow, and to analyze each region by the computationally optimum numerical technique for that region (ref. 8). Current codes use flow models which have been derived from open separation bubble data for the separation region and, primarily, from backward-facing step data for the flow at and downstream from reattachment. Within the separation bubble Gosman (ref. 9) noted that insufficient reliable data exists to define the structure of the backflow region. He suggested that future experiments should be on large-scale models using laser anemometry or other quantitative directionally sensitive techniques. The present study was undertaken to provide such detailed data for the entire flowfield of a separated flow configuration relevant to gas turbine airfoil design. The overall objective was to provide a comprehensive data base from which the accuracy of existing models could be assessed and improved models could be developed.

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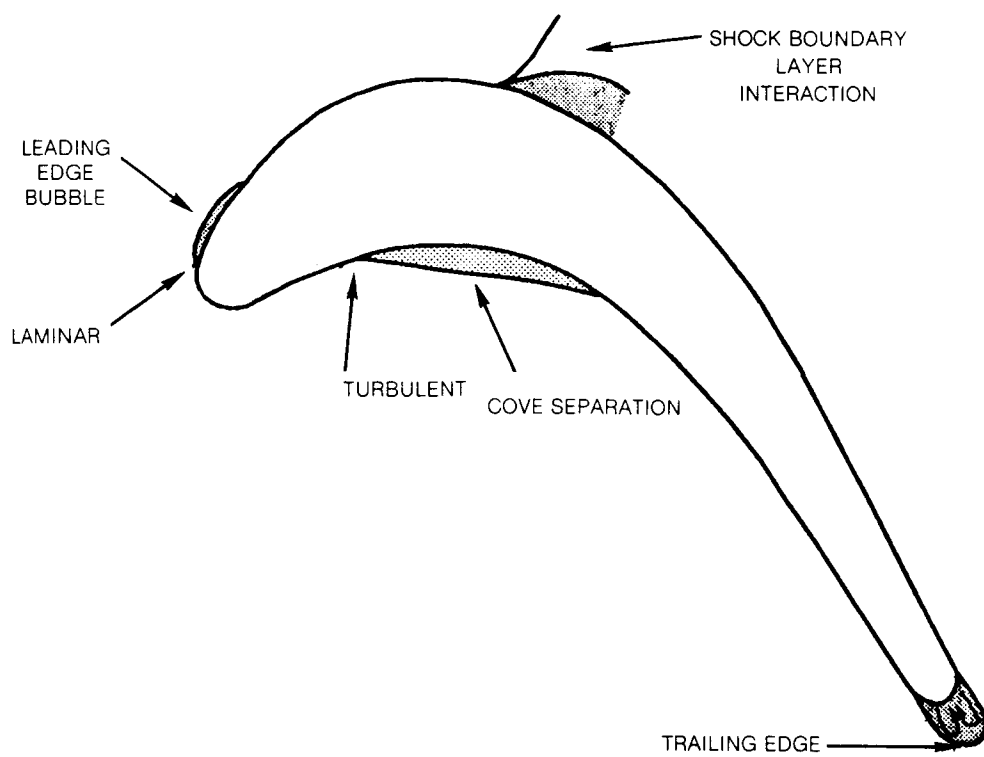


Figure 1-1 Airfoil Surface Separation

CHAPTER 2

REVIEW OF PREVIOUS INVESTIGATIONS

Detailed measurements of turbulent boundary layer separation and reattachment on a rotating compressor or turbine blade are unavailable because of the obvious difficulties of obtaining high resolution measurements in an operating engine environment. As noted in the previous chapter, only two experimental studies of the more tractible problem of turbulent boundary layer separation and reattachment on a stationary flat plate at low subsonic speed have been reported in the literature (refs. 5 and 6). Each of these studies, which yielded partial data bases, will be described below. To date, flow modelers have had to rely on the extensive body of literature which exists for both reattaching and separating turbulent flows.

Subsonic turbulent flow reattachment has been reviewed by Mueller (ref. 10), Bradshaw and Wong (ref. 11), and more recently by Eaton and Johnston (ref. 12). Eaton and Johnston noted that at the time of Bradshaw and Wong's review in 1972 very few reliable data for reattaching flows were available. Although details of reattachment length and mean flow profile development downstream of reattachment were known with good accuracy, turbulent stress data required to develop turbulence models were sparse. Since that time the development of laser velocimetry and pulsed-wire anemometry has enabled several investigators (refs. 13-17) to obtain reliable, quantitative reattachment data. Details of these investigations will not be reviewed in this section although pertinent studies such as those by Chandrsuda and Bradshaw (ref. 18), Driver and Seegmiller (ref. 14), and Westphal, et al. (ref. 17) will be discussed in Chapter 5, "Analysis and Discussion".

Ota and his colleagues (refs. 19-21) have studied separation bubbles having turbulent reattachment which form at the leading edge of blunt flat plates and circular cylinders aligned with the flow. These flows have a negligible boundary layer thickness at separation and therefore are unaffected by upstream boundary layer history as can be the case for backward-facing step flows. Ota, et al. studied the redeveloping boundary layer downstream of reattachment and found strong similarities between their data and the backward facing step data of Bradshaw and Wong (ref. 11), Mueller, et al. (ref. 22), and others.

Between the pioneering efforts of Sandborn and Kline (ref. 23) in defining turbulent separation criteria and the recent definitive experimental studies of Simpson and his colleagues (refs. 2-4), numerous studies of turbulent boundary layer separation have been reported in the literature. These studies have been reviewed by Simpson (refs. 8 and 24) and except for the

studies of Simpson and his colleagues (refs. 1-4) and a later study by Smith, et al. (ref. 25) will not be discussed in this section. However, as noted above for the turbulent reattachment data, pertinent studies will be included in the data comparisons presented in Chapter 5, "Analysis and Discussion".

Little reliable quantitative data was obtained within turbulent separated boundary layers prior to 1974 due to a lack of proper instrumentation. Simpson, et al. (ref. 1) pioneering effort in applying a one-component directionally sensitive laser velocimeter to the study of separating turbulent airfoil-type boundary layers revealed several new features of these flows including the following:

- (1) Law-of-the-wall velocity profile scaling is valid up to intermittent separation.
- (2) Intermittent separation occurs when the wall static pressure gradient begins to diminish.
- (3) Normal stress terms in the momentum and the kinetic energy equations are important near separation.
- (4) The separated flowfield shows some similarity of the streamwise mean velocity, the streamwise turbulence component, and the forward flow fraction.

Later studies by Simpson and his colleagues using a two-component LV system culminated in a series of three papers (refs. 2-4) which presented fundamental mean flow and turbulence structure data from which improved models of the backflow region could be developed. Several significant conclusions resulted from these studies including the following.

- (1) The backflow velocity profiles are not consistent with law-of-the-wall type scaling. Simpson (ref. 26) postulated a universal mean backflow velocity profile scaled on the maximum negative mean velocity U_N and the distance, N , of the maximum negative mean velocity from the wall.
- (2) Within the backflow the turbulent velocities are comparable to the mean flow velocities although the turbulent shearing stresses are low.
- (3) Mixing length and eddy viscosity models are physically meaningless in the backflow and have reduced values in the outer region of the separated flow. Reynolds shearing stress must be modeled by relating it to the turbulence structure and not the mean flow

gradients because the mean backflow velocities are obtained by time-averaging large turbulent fluctuations and are not related to the source of the turbulence.

- (4) A three-tiered structure was apparent in the backflow. It consisted of a viscous layer closest to the wall, a wider flat intermediate layer, and an outer backflow region which was part of the large-scaled outer region flow.

Later work by Simpson has been directed toward obtaining an understanding of unsteady separating turbulent boundary layers (ref. 27).

Smith, Hastings, and Williams (ref. 25) studied the structure of an equilibrium separated boundary layer on a flat plate with a single component LV system. The boundary layer was first accelerated and then decelerated such that the boundary layer edge velocity varied with distance according to a negative power law (i.e., $U = Cx^{-m}$). Mean axial velocity and turbulence intensity profiles were measured at several axial stations and one pair of profiles of the mean transverse velocity and turbulence intensity were measured in the separated region. Static pressures were measured on the test surface centerline. Forward flow fraction and shear stress profiles were not measured.

Equilibrium separated flow was maintained for 1.1 m before the boundary layer on the test surface and tunnel ceiling merged. Some flow asymmetry was noted and measurements indicated that the flow was not in strict two-dimensional equilibrium. However, boundary layer displacement and momentum thickness grew linearly as expected for equilibrium flow.

Limited measurements of backflow velocity profiles were presented. Data scatter appeared to be considerable near the test surface although no estimate of measurement error was presented. Smith, et al. corroborated Simpson's finding that the backflow velocity profile could not be modeled using the universal law-of-the-wall. They also concluded that normal Reynolds stresses were considerably more important in the momentum integral equation than would be expected on the basis of equilibrium attached flow.

In addition to the separated turbulent boundary layer studies of Simpson and his colleagues and Smith, et al., only two experimental studies of turbulent boundary layer separation with reattachment on a flat plate have been reported in the open literature. These studies were conducted as Ph.D. dissertations by B. D. Fairlie under A. E. Perry at the University of Melbourne in 1973 (ref. 5) and by A. D. Cutler under J. P. Johnston at Stanford University in 1984 (ref. 6).

Perry and Fairlie (ref. 5) separated an equilibrium turbulent boundary layer to generate a large separation bubble (41 cm long x 8 cm thick at the maximum height of the dividing streamline) on the floor of a low speed open-return wind tunnel. The test section had a rectangular cross section measuring 61 cm long x 11 cm high at the inlet. It was 2.5 m long with a specially constructed flexible roof, allowing any desired streamwise pressure gradient to be obtained. The variable tunnel outlet height was set at approximately 60 cm for the two test cases reported in ref. (5). A false roof mounted below the flexible roof was used to provide a starting point for a new roof boundary layer thereby inducing the flow to preferentially separate from the flat test surface. Smoke, tufts and surface flow visualization indicated moderate three-dimensionality in the flowfield.

Mean velocity, flow angle, and surface static pressures were measured throughout the flowfield. Neither forward flow fraction, turbulence, nor shear stress data were reported. The surface static pressures obtained on the floor centerline showed a pressure plateau over a 37 cm long region under the bubble with pressure maxima at the separation and reattachment points. Velocity traverses were made normal to the plate on the duct centerline throughout the flowfield. Data was obtained with flattened pitot probes upstream of separation. Near separation and within the separation bubble a twin hot-wire probe was used to obtain mean-velocity and flow angle measurements. Flow angles were obtained by traversing a temperature sensitive wire through the wake of the velocity sensitive wire. As reported by Perry and Fairlie, this intrusive hot-wire probing technique is inaccurate in highly unsteady flows or regions having intermittent flow reversals due to signal rectification by the velocity sensitive wire. Reported velocity profiles showed discontinuities at the edge of the backflow region. The velocity profiles indicated strong backflow within the separation bubble. However, the strength of the backflow could not be quantified without forward flow fraction data.

Cutler and Johnston (ref. 6) studied the effect of the state of equilibrium or disequilibrium of the inlet turbulent boundary layer on separation and reattachment on a flat plate. Tests were conducted in a low speed closed-return wind tunnel having a 30.48 cm wide rectangular test section which diverged over a 1 m length from an inlet height of 10.16 cm to an outlet height of approximately 40 cm. Boundary layer bleed slots on the upper diverging wall caused the flow to preferentially separate from the lower wall flat plate test surface. Measurements were made of wall static pressure distributions, forward flow fraction at the wall using a thermal tuft, total pressure profiles with pitot probes, and mean velocity and turbulence parameters using normal and crossed hot-wire probes.

Complete detachment of the boundary layer was not achieved in the Cutler and Johnston test cases. The test surface boundary layer passed through incipient detachment, closely approached detachment, and then fully reattached. The minimum value of the forward flow fraction measured at the wall was 0.59. Careful conditioning of the flow ensured excellent flow two-dimensionality in the inlet flow. Nevertheless nonnegligible three-dimensional effects were evident near detachment and reattachment when the terms in the two-dimensional momentum integral equation were evaluated using experimental data.

Cutler and Johnston drew several significant conclusions from their study including the following:

- (1) A tripped boundary layer which had not recovered to an equilibrium profile separated further downstream than a boundary layer having an equilibrium profile at the same operating conditions.
- (2) Since mean streamline angles to the wall are not small near the separation region even though the wall is flat it becomes important to model flow quantities, particularly turbulent shear stress, in coordinates locally orthogonal to the streamline.
- (3) Mean streamline convex curvature becomes significant between the detachment and reattachment locations, even though the wall is flat. The effect of the streamline curvature is to reduce the shear stress and the entrainment of the freestream fluid into the boundary layer and to induce nonnegligible static pressure gradients normal to the flat wall.
- (4) To calculate flows downstream of a reattachment, the development of mean-velocity-profile quantities and of turbulence quantities must be modeled separately because there is no unique relationship between these quantities.

CHAPTER 3

DESCRIPTION OF THE EXPERIMENT

3.1 Experimental Arrangement

3.1.1 Wind Tunnel Arrangement

The experiment was conducted in the UTRC Boundary Layer Wind Tunnel which is shown schematically in figure 3-1. It is a low speed wind tunnel of recirculating design and consists of a blower, settling chamber/plenum, contraction nozzle, boundary layer bleed scoop, boundary layer test surface, downstream diffuser, coarse air filter, temperature control heat exchanger, and return duct. This tunnel has been designed to produce large scale two-dimensional boundary layers with Reynolds numbers, freestream turbulence levels and pressure coefficient distributions typical of turbomachinery blades. A thorough calibration of the flow characteristics of the tunnel (ref. 28) has shown the flow to be highly two-dimensional and steady. The freestream turbulence level can be varied between 0.25 percent and 10 percent with the addition of turbulence generating grids.

For this test program several modifications were made to the tunnel as shown in figure 3-2. The major modification was the installation of a new test section, described below, which was designed to produce a large two-dimensional turbulent separation bubble. Another major modification was the addition of a submicron filtration system downstream of the diffuser section to permit LV seeding in the test section without contamination of the fine mesh screening in the settling chamber.

The 1.83 m x 1.83 m cross-section submicron filtration system consisted of nine filtration modules arranged in parallel in a 3 x 3 matrix. Each 0.61 m x 0.61 m cross-section filtration module consisted of a prefilter, a bag filter, and an absolute HEPA filter. Tests of a single filter module indicated that the filtration system was extremely efficient. Under conditions of heavy LV seeding the air in the return duct was found to be two orders of magnitude cleaner than the ambient unseeded air circulating in the unmodified tunnel. The filtration system had a nominal 3 cm H₂O pressure drop at the 283 SCMM (10,000 SCFM) tunnel operating condition used in the test program.

Several other modifications were made downstream of the contraction nozzle. The leading edge bleed scoop was covered by a contoured wall section (see inset in fig. 3-2) and the original boundary layer test surface was used as a boundary layer development section. The downstream horizontal variable angle diffuser was then replaced by the new diffusing test section. An

0.64 cm square bar was installed downstream of the contraction nozzle to provide a two-dimensional boundary layer transition process. The axial location of the trip was 245 cm upstream of the test section inlet (i.e., $x = 0$).

3.1.2 Test Section Arrangement

The test section consisted of a constant area approach section which functioned as a continuation of the boundary layer development section, a diverging section to produce the large adverse pressure gradient required to separate the turbulent boundary layer from the test plate, a converging section to force its reattachment and a constant area exit duct. The fixed dimensions of the test section were: length, 152 cm (60 in.); width, 86.4 cm (34 in.); inlet height, 21.3 cm (8.38 in.); exit height, 15.2 cm (6 in.).

The upper wall test surface was fabricated from 1.27 cm thick aluminum tooling stock. The plate was machine ground and hand buffed with steel wool to ensure surface smoothness. The lower wall was fabricated from 1.27 cm thick aluminum plates joined by flexures. The joints between the flexures and the aluminum plates were fabricated to eliminate steps in the surface contour. The lower wall was moveable by means of jack screws. During shakedown testing the lower wall geometry was adjusted over a wide range until a large separation bubble having a minimum amount of three-dimensionality and unsteadiness was achieved on the test surface. Photographs of the final test section configuration selected for the experiment are shown in figures 3-3 and 3-4.

3.1.2.1 Boundary Layer Bleed System

Boundary layer bleed on the test section diverging wall was used to prevent the preferential separation of the turbulent boundary on this surface. Test surface corner bleed was also used to improve two-dimensionality of the test section flowfield. The bleed system was driven by natural suction caused by a static pressure differential between the test section and the inlet to the submicron filtration system. A 22.9 cm H_2O pressure differential was created by installing two 40 percent open perforated plates in series just upstream of the turning vanes ahead of the vertical diffuser section to raise the static pressure in the test section.

The diverging lower wall was equipped with two bleed scoops which spanned the width of the test section as shown in the photograph in figure 3-3. The scoops were designed to force the lower wall boundary layer to remain attached throughout the strong adverse pressure gradient field required to produce two-dimensional separation on the test surface. The first scoop, which had a fixed height of 2.87 cm, could be moved axially, parallel to the lower wall, over a 22.9 cm. range. The second scoop which could be moved axially and vertically as well as rotated was found to be unnecessary and remained closed

during the experimental program. Approximately 30 percent of the flow entering the test section was removed by the operational lower wall bleed scoop.

The upper wall bleed system consisted of two .32 cm wide, 152 cm long, suction slots on either side of the test surface at the corner between the test plate and side wall. The purpose of these bleed slots was to improve the two-dimensionality of the flow near the test surface by removing low momentum fluid caused by the sidewall boundary layers. Each bleed slot was connected to a plenum located above the test section (fig. 3-5) by fifteen 2.54 cm dia. holes drilled through the test plate support structure. Partitions in the bleed slots and the plenums divided each suction slot into three axial segments each having independent control of suction strength by means of valving. Bleed flow was ducted from the plenums to the filter inlet by a 10 cm dia PVC pipe. Less than one percent of the flow entering the test section was removed by the upper wall bleed system. Prior to installing the corner bleed slots, sidewall fences were used in an attempt to improve flow two-dimensionality in the test section. The fences, made of 20 cm x 70 cm float glass, were mounted approximately 3 cm from the sidewalls on standoffs which permitted adjustment during rig operation. The fences were found to be only moderately successful in reducing flow three-dimensionality.

3.1.2.2 Test Section Instrumentation

The test section instrumentation consisted of 140 wall static pressure taps and 75 0.63 cm dia. probing ports. Of these 120 of the wall static taps and 55 of the probing ports were located on the test surface. As shown in figure 3-5, the static taps were arranged in three rows of forty located on the test section centerline and 15.2 cm to either side of the centerline. In addition 35 of the probing ports were located on the centerline and 10 on either side of the centerline (figs. 3-6 and 3-7). The remaining 20 wall static taps and 20 probing ports were located along the centerline on the lower wall of the test section. The probing ports on the test surface were used for traversing total pressure probes and hot-film probes normal to the test surface to obtain flowfield data. Specific locations of the ports, which were machined into the test surface after the position of the separation bubble was established during shakedown testing, are described in detail below. Probing ports on the lower wall were used for traversing total pressure probes normal to the surface. These data permit calculation of the displacement thickness development and hence define the lower bounding streamline for CFD codes. Additionally, one sidewall of the test section was fabricated from float glass to facilitate LV measurements.

3.2 Test Program Definition

3.2.1 Selection of Measured Variables

Directly measured and derived variables were selected based upon code assessment requirements. A viscous-inviscid calculational procedure for predicting two-dimensional boundary layer separation and reattachment on a flat plate requires input data to permit calculation of both the potential flow-field within the test section and the viscous flow along the test plate. The freestream velocity at the test section inlet and the location of the bounding streamline along the lower wall opposite the test surface were required as boundary conditions for use in the potential flow solution. The integral boundary layer parameters (displacement thickness and momentum thickness) and the Reynolds number based on momentum thickness at the test section inlet were required to define the initial station for the viscous calculation. Depending on the complexity of the turbulence model used, the Reynolds stress distribution at the test section inlet may also be needed to initialize the model. The desired output of the calculational procedure is a complete specification of the mean velocity field and static pressure distribution throughout the test section, and depending on the turbulence model used, some turbulence field properties.

Based on these and experimental considerations, axial and vertical mean velocity components, total pressure, wall static pressures, and inlet total temperature were selected as the mean variables to be measured directly. Turbulence quantities measured directly were: the axial component of turbulence intensity, $\sqrt{u^2}$; the vertical component of turbulence intensity, $\sqrt{v^2}$; and the Reynolds stress, \overline{uv} . Turbulence spectra were taken to document the unsteady nature of the separation bubble. In addition, the forward flow fraction, γ_{p_u} , the fraction of the time the flow moves downstream, and the transverse flow fraction, γ_{p_v} , the fraction of the time the flow moves away from the test surface, were selected for measurement to define the zones of separation and reattachment and to delineate the regions where hot-film and total pressure measurements would be reliable.

3.2.2 Tunnel Operating Conditions

The test conditions for the experiment were selected based upon two criteria: the turbulent separation bubble should be large enough to provide high resolution of bubble details and the Reynolds number of the turbulent boundary layer on the test surface at the test section inlet should be in the range applicable to gas turbine airfoils. Establishment of a large separation bubble was achieved by providing a diverging-converging test section of 150 cm axial extent and a suitably scaled test section height. Reynolds number simulation was established by producing a turbulent boundary layer having a Reynolds number based on momentum thickness of 15,000 at the test section

inlet at the inlet velocity of 27 m/sec. This value is typical for aircraft turbine blades at the onset of cove separation.

Separation bubble reproducibility (stationarity) throughout the duration of the test program was ensured by adjusting the operating conditions to achieve the same Reynolds number for each test run. This was achieved by adjusting the tunnel dynamic head, Q , to compensate for changes in barometric pressure and tunnel temperature. The dynamic head was determined from the difference between the total pressure measured with a kielhead probe located in the core flow of the boundary layer development section and a wall static pressure measured at the same axial location. Tunnel air temperature was measured with a Cr-Al sheathed thermocouple inserted through an insulated plug in the tunnel sidewall. The tunnel dynamic head was adjusted mainly for changes in barometric pressure and to a lesser extent for tunnel temperatures. The tunnel temperature varied from 22 to 27 deg C between winter and summer testing but on any given day the tunnel temperature could be maintained constant to within ± 0.5 deg C.

3.2.3 Selection of Measurement Locations

To meet the code assessment objectives, a "benchmark" study of two-dimensional turbulent boundary layer separation and reattachment on a flat plate must, as a minimum, provide the input data required to perform the computation and sufficient flowfield data at relevant locations to determine prediction accuracy. Supplementary data should also be obtained to assess experimental accuracy and to document flow two-dimensionality.

To perform the calculation, data must be obtained at an initial measurement plane to start the computation and at a sufficient number of stations to define a bounding streamline. A plane normal to the upper wall, located in the boundary layer development section 24 cm upstream of the test section inlet, was selected as the initial measurement plane. The wall static pressure on the test surface and a 70-point total pressure traverse normal to the test surface were used to define the one-dimensional mean velocity profile at this location. A 34-point hot-film traverse was also used to determine the axial turbulence intensity profile. To determine the coordinates of a bounding streamline, wall static pressures and total pressure profiles normal to the wall were measured at 20 stations along the lower wall on the tunnel centerline (fig. 3-6). The measurement increment normal to the wall was chosen to yield a minimum of 20 points in each total pressure traverse.

To assess the accuracy of the code predictions and to acquire a detailed understanding of the flowfield upstream, within, and downstream of the separation bubble, a dense array of static pressure taps and traverse locations was provided on the test plate as shown in figure 3-7. Wall static pressure taps

extended the length of the test plate from the upstream zero-pressure gradient region to the corresponding region downstream of separation. Thirty-six traverse stations were located on the tunnel centerline (Table 1). Twelve stations were located upstream of separation, five within the intermittent separation zone, eight within the reversed flow region, five within the intermittent reattachment zone, and six downstream of separation. Ten additional traverse stations were located on a line 15.2 cm to either side of the tunnel centerline to document flowfield two-dimensionality. Two of the off-centerline traverse stations were located in each of the five distinct flow regions on the test plate.

On the tunnel centerline, total pressure traverses were made at each of the 36 measurement stations, single-element hot-film probe traverses were made at 30 stations, and LV traverses to measure axial and vertical velocity components were made at 16 stations, as shown in figure 3-7. Along the line located 15.2 cm to either side of the tunnel centerline, total pressure traverses were made at each of the 10 measurement stations, single-element hot-film probe traverses were made at 8 stations, and LV traverses were made at four stations. Except for off-centerline LV data taken at the $x = 26.7$ cm ($x = 10.5$ in) station, each LV traverse station coincided with a hot-film traverse station, and each hot-film traverse station coincided with a total pressure traverse station. An additional 20 LV traverses were made at 14 centerline stations and six off-centerline stations, as shown in figure 3-7, to measure Reynolds stress.

The measurement increment normal to the test surface was varied based on resolution requirements. Fine resolution was necessary for defining the velocity field in the near-wall region since this is critical for code assessment. Additional detail was considered desirable to demarcate the edge of the reversed flow region. Since more than 300 traverses were planned in this experiment, regular, fine, and extra fine increment schedules were defined to limit the number of data points required to produce the desired resolution. The regular increment schedule was sufficiently dense to provide a minimum of 10 LV and 20 hot-film or pitot measurements per traverse. It was used for all hot-film measurements and LV Reynolds stress measurements and for pitot and LV velocity measurements at off-centerline locations to document flow two-dimensionality. The fine increment schedule, which provided sufficient detail in the near-wall region to produce a 30- to 40-point traverse, was used for all LDV velocity measurements on the tunnel centerline and most off-centerline pitot measurements. The finest increment schedule, which produced a 50- to 80-point traverse, was used for pitot traverses to define the boundary layer throughout the test section along the test plate centerline and at off-centerline locations near the test section inlet.

In selecting the measurement matrix described above, it was recognized that pitot and hot-film measurements could be inaccurate in regions of high turbulence intensity and would not be meaningful in regions having intermittent flow reversal more than a few percent of the time. The LV measurement locations were selected to define such regions and therefore permit the pitot and hot-film measurements to be interpreted correctly. In regions where the pitot measurements were valid, finer resolution of the near-wall velocity field was obtained. In conjunction with the LV mean velocity measurements, pitot data provided a means to estimate the static pressure field within the flow. In regions where the hot-film measurements were valid, turbulence spectra were acquired to contribute to an understanding of the unsteady nature of the turbulent separation bubble. In addition, the measured components of mean velocity and rms turbulence intensity provided a redundant set of data to check the LV measurements.

3.2.4 Flow Two-Dimensionality and Steadiness Criteria

Objectives were identified at the outset of the experiment regarding spanwise uniformity of the flow at the initial measurement plane and at three measurement planes in the test section: at the test section inlet, just upstream of separation, and within the reversed flow region. The spanwise uniformity criterion at the initial measurement plane was defined as deviation of less than one percent in the measured pitot pressure at tunnel midheight during a traverse across the tunnel (excluding a 7.6 cm region at each sidewall). Within the test section the criterion for spanwise uniformity of the flow at each measurement plane was agreement to within five percent of the boundary layer integral properties measured on the test plate centerline and at stations 15.2 cm to either side of the centerline.

Criteria were also defined relative to the two-dimensionality of the separation line and for steadiness of the flow in the test section. A satisfactory two-dimensional separation was defined as a separation line deviating from a straight line by less than 5 percent of the test section span excluding a 7.6 cm region at each sidewall. The criterion for flow steadiness in the test section was defined as the absence of intermittent flow reversal on the contoured wall opposite the test plate and on the test plate outside the separated flow region as indicated by surface mounted tufts.

3.3 Instrumentation

3.3.1 Laser Velocimeter System

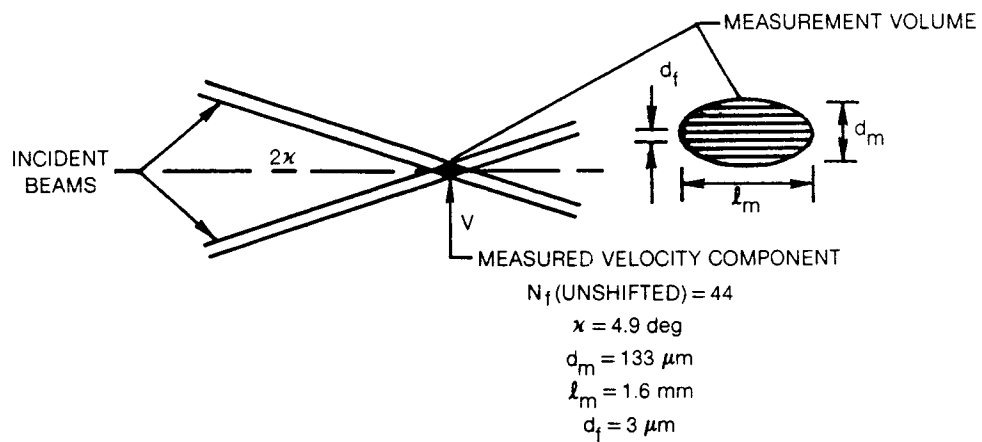
The LV system (fig. 3-8) is described in detail in Appendix A. The system consisted of a 2W argon-ion laser, backscatter optical system, counter-

type signal processor, computer for on-line data reduction, and a hard disk storage device for subsequent off-line data reduction. All system components are commercially available.

The LDV was operated in a dual beam or "fringe" mode in which light from the intersection of two incident beams having a wavelength of $0.5145 \mu\text{m}$ is heterodyned to detect the Doppler shift from an injected seed particle, at the local, instantaneous fluid velocity. In this mode, the LV measures the velocity component in the plane of the incident beams that is perpendicular to the bisector of the beams. The effective shape of the resultant measurement volume is an ellipsoid with major axis in the direction of the bisector of the beams. Sketch A below shows these features and the theoretical measurement volume dimensions assuming that the ellipsoidal surface is defined by the locus of points where Doppler signal amplitude is $1/e^2$ of its centerline value. No direct measurements of the effective measurement volume dimensions were made; they can be affected by signal amplitude and the signal processor threshold level setting. To obtain maximum resolution, the major axis was aligned in the spanwise direction. Resolution of the LV system was high when compared to the relevant dimensions of the experiment. The minor axis of the measuring ellipsoid, d_m , was $1/850$ of the inlet boundary layer thickness and the major axis, l_m , was $1/560$ of the test section width.

The optical system used a 3.75X beam expander, a relatively wide angle lens ($\kappa = 4.9 \text{ deg}$), and 152 mm dia. optics to produce a sufficiently high signal/noise ratio (SNR) to permit measurements to be made in the backscatter mode. A Bragg cell was used to eliminate directional ambiguity and to provide a 360 deg acceptance angle.

The counter-type signal processor featured user selectable measurement mode, fringe count, validation accuracy, input gain, threshold level setting, and large amplitude signal rejection level. The processor was operated in the continuous (CONT) mode in which a measurement is made each time the minimum number of fringes is counted. The CONT mode was chosen to counter the effects of individual realization biasing (see discussion in Appendix C). Optimal histograms and fast data rates were achieved with the fringe count selector set at 32 and the accuracy limit for data validation set at 2%. The signal gain and large amplitude signal rejection level were adjusted to reject 10 to 25% of the Doppler bursts to ensure that particle lag biasing (which could be caused by large seed particles in the tail of the seed particle size distribution) was eliminated. Data rates of validated signals ranged from 20/sec to more than 2000/sec depending on the region of the flow being measured. Based upon the uncertainty analysis in Appendix C and the large turbulence levels generated by the separation bubble, 2000 samples were acquired per data point to generate velocity histograms for mean velocity and turbulence intensity measurements. For Reynolds stress measurements the previously measured local



Sketch A — LDV Beam Arrangement

turbulence intensity was used to determine whether 2000, 4000, or 8000 samples per data point were required to obtain the desired accuracy. Additional details concerning LV data processing are given in Appendix A.

Titanium dioxide powder having a nominal particle size of 1.0 μm dia was dispersed into the tunnel airstream to provide highly reflective light scattering centers for LV measurements using the seeding system described in Appendix A. A mixture of titanium dioxide powder and Cab-O-Sil, a silica deagglomerating agent was fluidized in a low pressure seeder and injected into the tunnel just downstream of the aftermost turbulence suppression screen using a seeder probe designed to minimize the disturbance to the tunnel airstream. Particle lag calculations and LV velocity measurements across a normal shock using similar seeding material (see Appendix C) indicated the 1.0 μm dia titanium seed particles would follow the mean flowfield variations with a lag of less than 0.3 percent throughout the test section. Less than 1 percent error in turbulence intensity was anticipated for turbulence fluctuations below 2.9 KHz.

3.3.2 Total Pressure Instrumentation

The total pressure measurement system, shown in figure 3-9, consisted of total pressure probes described below, a probe traverse system, pressure transducers, signal conditioners and amplifiers, averaging voltmeters, a data logger, an on-line computer, and a micromanometer. The probe traverse system, described in reference 28, consisted of an ball/screw traverse drive suspended on a linear ball bearing track above the test section. Three 0-0.5 psid pressure transducers were used to measure total pressure, test section wall static pressure, and the tunnel dynamic pressure. Transducers were calibrated each day with the micromanometer. The measured pressures were averaged for 100 sec using averaging voltmeters and were recorded together with the tunnel temperature on a data logger.

Two sets of specially designed pitot probes, shown in figure 3-10, were used for total pressure traverses. The two sets, which differed only in the offset distance (1.27 cm or 1.91 cm) from the sensing face to the probe shaft centerline, each consisted of a boundary layer probe for near wall measurement and a kielhead probe for midstream measurements. The boundary layer probe was constructed from .081 cm dia stainless steel tubing flattened to an oval cross-section at the probe face having major and minor axes of 0.122 cm and 0.043 cm respectively. A 0.64 cm dia. brass sleeve plugged the probing port during near wall traversing and was pushed out by and locked into the probe shaft for the remainder of the traverse. The kielhead probe was fabricated from a 0.159 cm dia. aspirated kielhead tube soldered into a 0.064 cm dia. probe shaft. The aspirated kielhead tube contained four 0.038 cm dia. holes equally spaced around its periphery at a distance of 0.191 cm downstream from

the probe face and a concentric inner sensing tube (0.038 cm ID). The four aspiration holes functioned in the same manner as the open back end of a conventional kielhead probe by permitting a through flow of air past the sensing tube. The kielhead tube was bent into alignment with the midrange of the mean flow directions anticipated during a traverse to ensure that the flow direction relative to the probe face was within the ± 30 deg acceptance angle determined during probe calibration.

3.3.3 Hot-Film Instrumentation

The hot-film measurement system consisted of a single element hot-film probe, a commercially available constant temperature anemometer system (including a fourth-order polynomial linearizer and a signal conditioner containing high- and low-pass filters), two rms voltmeters to time average the mean and fluctuating output signals, and a spectrum analyzer. The single-element hot-film probes (fig. 3-11) each used an 0.051 cm dia. cylindrical sensor to measure the streamwise mean velocity and turbulence components. Frequency response of the anemometer system was measured to be 65 KHz in a 27.5 m/sec airstream at the 1.5 overheat ratio used in the test program. The unique design of the probe was necessitated by the desire to insert the probe through the same wall on which boundary layer velocity profiles were to be measured. A pin through the probe stem set the minimum stand-off distance at 0.127 cm. In the unbraced configuration supplied by the vendor severe "ringing" caused by vibration of support needles was noted during probe calibration. Nonmetallic braces were used to stiffen the support to eliminate ringing.

3.3.4 Flow Visualization

Flow visualization was accomplished during shakedown testing with surface-mounted tufts, "tuft trees", surface flow visualization, and smoke. Tufts were mounted on the test surface in a dense 10 x 14 array to monitor the size and two-dimensionality of the separation bubble, on the diverging wall opposite the test plate to check that the flow remained attached, and on the tunnel sidewalls. A 3 x 3 array of "tuft trees" was mounted vertically between the lower tunnel wall and static pressure taps in the test plate. The "tuft trees" were constructed from stiff 0.089 cm OD stainless steel tubing over which swivel-mounted tufts were slipped and secured in place by short lengths of shrink-fit tubing. Approximately 10 tufts were positioned on each "tree" to visualize the flow in the vicinity of the separation bubble and to estimate the bubble thickness. Surface flow visualization was achieved by injecting red low-viscosity fluid through static pressure taps in the test plate. The smoke flow visualization system, described in reference 29, used a traversible probe upstream of the test section inlet to produce ammonium sulfite smoke by impinging gaseous jets of anhydrous ammonia and sulfur dioxide within the tunnel airstream.

3.4 Measurement Approach

3.4.1 Total Pressure and Hot-Film

Total pressure and hot-film traverses were aligned normal to the test plate. The total pressure traverses were conducted using boundary layer probes over the range 0.025 cm to 5.08 cm from the test plate and kielhead probes were used from 2.54 cm from the plate to the vicinity of the opposite wall. During the total pressure traversing phase, which was conducted before the flowfield had been defined by LV measurements, the flow direction near the reversed flow region was not known a priori at each point in space. Therefore, two sets of traverses were conducted to obtain a complete set of data at each measurement plane. One set of traverses was made with probes facing upstream and the second set made from the adjacent upstream traversing port with the probes facing downstream. Using probes with either 1.27 cm or 1.91 cm offsets to match the 2.54 cm or 3.81 cm probe port separation distance ensured probe face coincidence in the measurement plane. Hot-film traversing was conducted in a similar manner in the vicinity of the separation bubble.

After the hot-film anemometers were checked at the start of each day an additional linearizer adjustment was made to offset the effects of hot-film aging. The hot-film sensor was positioned at the $x = 7.6$ cm, $y = 10.2$ cm location in the tunnel where the streamwise velocity was known to equal 0.9925 of the freestream velocity calculated from rig operating conditions. After the linearizer output gain was adjusted to yield the desired velocity, the probe was moved to the next scheduled traverse location.

3.4.2 Laser Velocimeter

The four LV beam orientations, designated 0, 90, and ± 45 deg, used to measure U , V , $\sqrt{u^2}$, $\sqrt{v^2}$ and \overline{uv} are shown in figure 3-12. The direction of motion of the Bragg-shifted fringes is also indicated in the figure. In the 0 deg orientation the vertical fringes measure only the horizontal, U , velocity component. In the 90 deg orientation the horizontal fringes measure only the vertical, V , component. In the ± 45 deg orientations, $\sqrt{2} (U \pm V)$, is measured from which \overline{uv} can be obtained using the equations derived in Appendix B.

Because of the 9.8 deg included angle between the laser beams, the optical axis was inclined 5 deg relative to the horizontal test plate surface for measurements of V , $\sqrt{v^2}$ and \overline{uv} near the test surface ($y \leq 2.54$ cm). The inclination of the fringes relative to horizontal introduced a negligibly small uncertainty in the acquired velocity measurement due to the component of the transverse velocity. The 90 deg orientation measured $V \cos 5^\circ + W \sin 5^\circ$. The ± 45 deg orientations measured $\sqrt{2} (U \pm V \cos 5^\circ \pm W \sin 5^\circ)$. The data reduction equations required to extract V , $\sqrt{v^2}$ and \overline{uv} from these measured quantities are derived in Appendix B.

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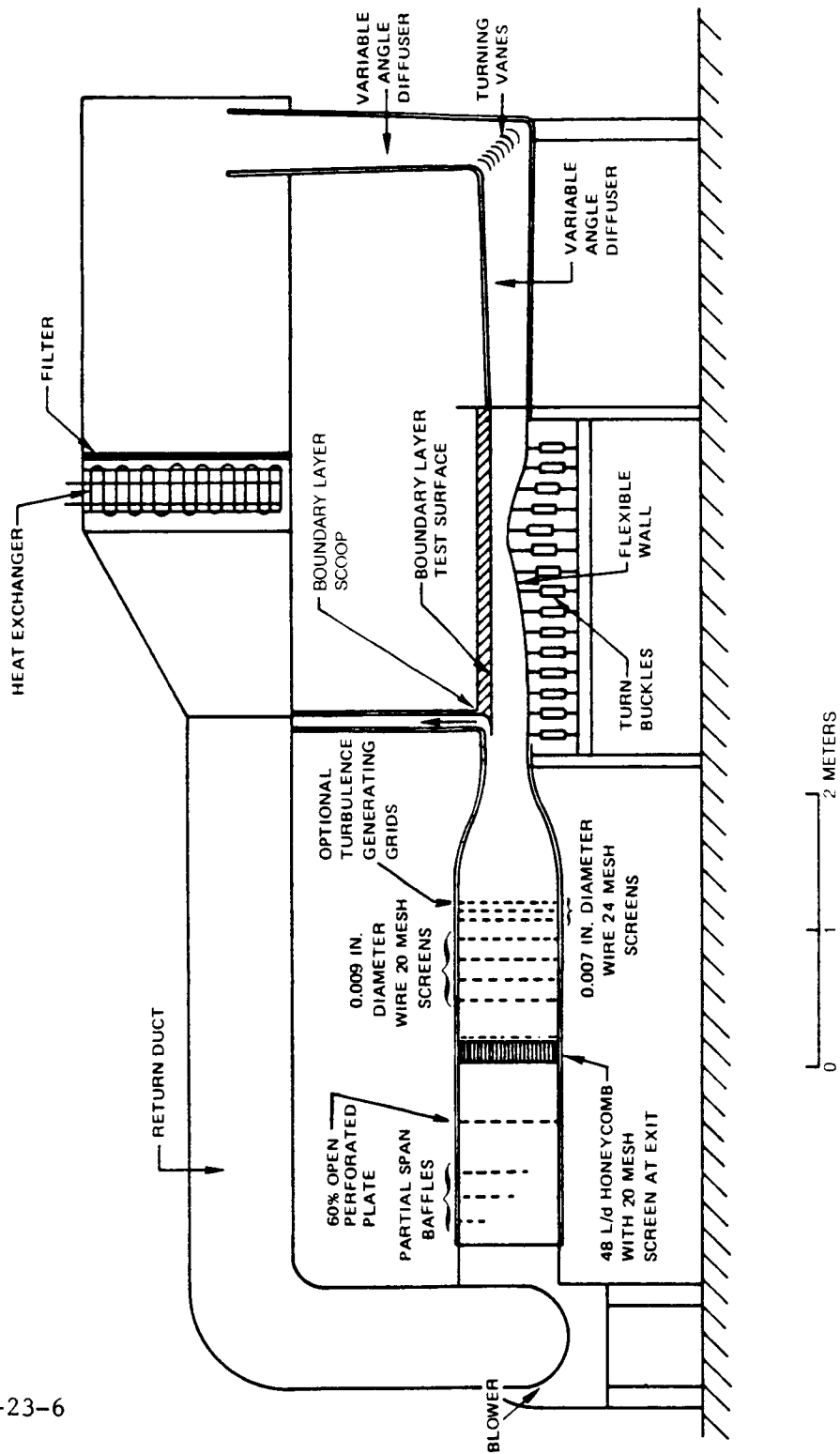


Figure 3-1 United Technologies Research Center Boundary Layer Wind Tunnel

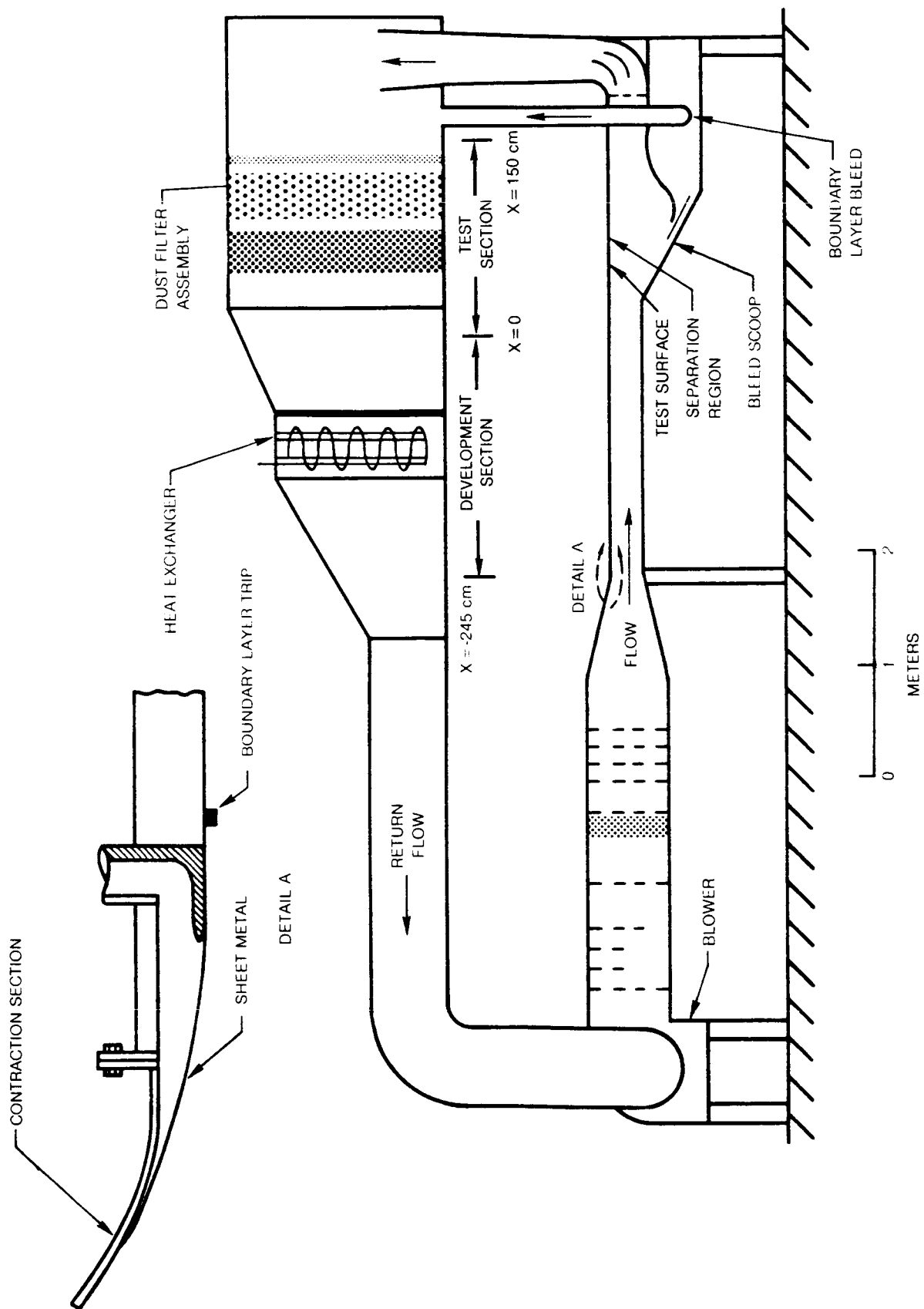


Figure 3-2 Modified Boundary Layer Wind Tunnel

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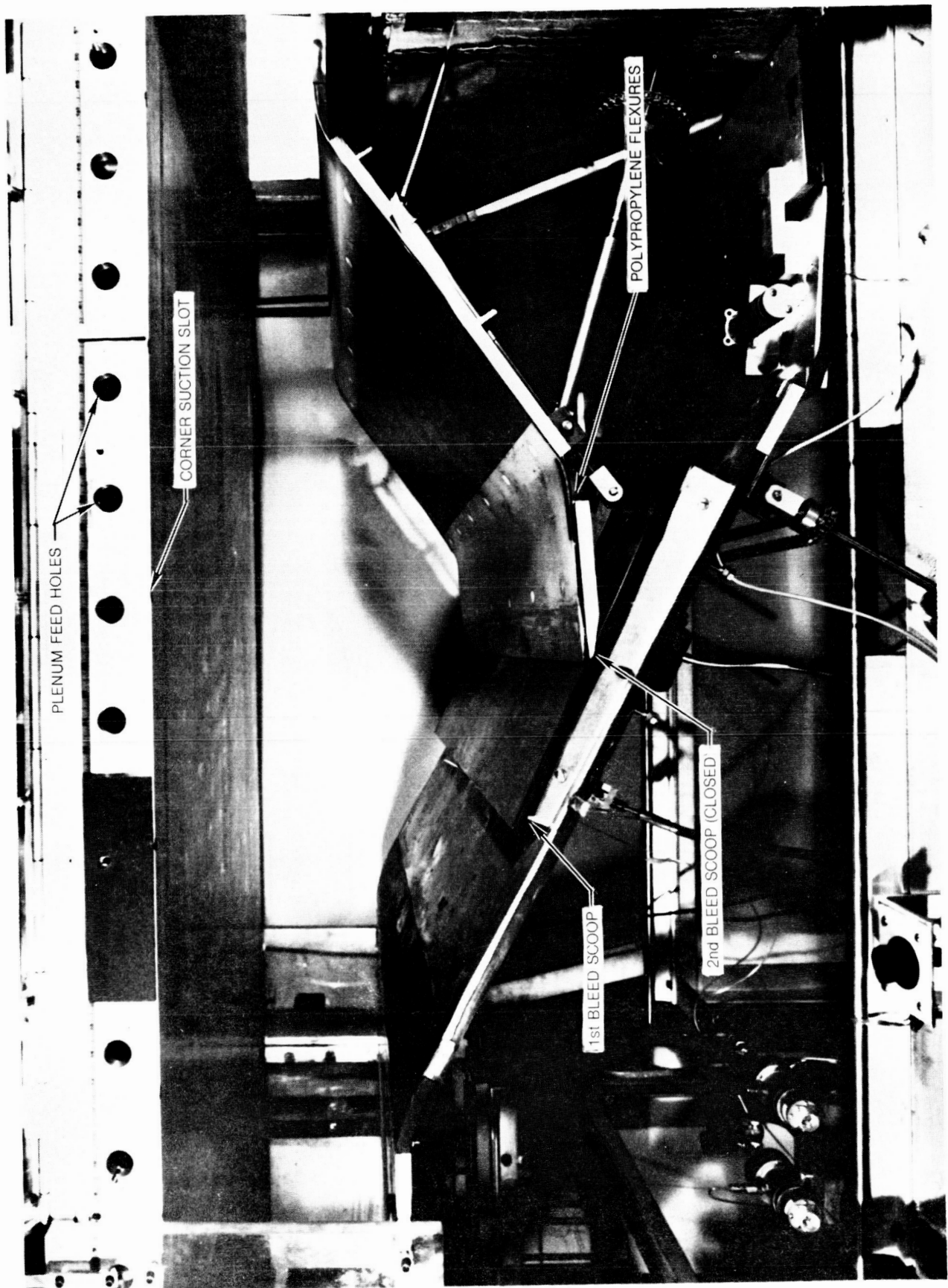


Figure 3-3 Turbulent Boundary Layer Separation Test Section

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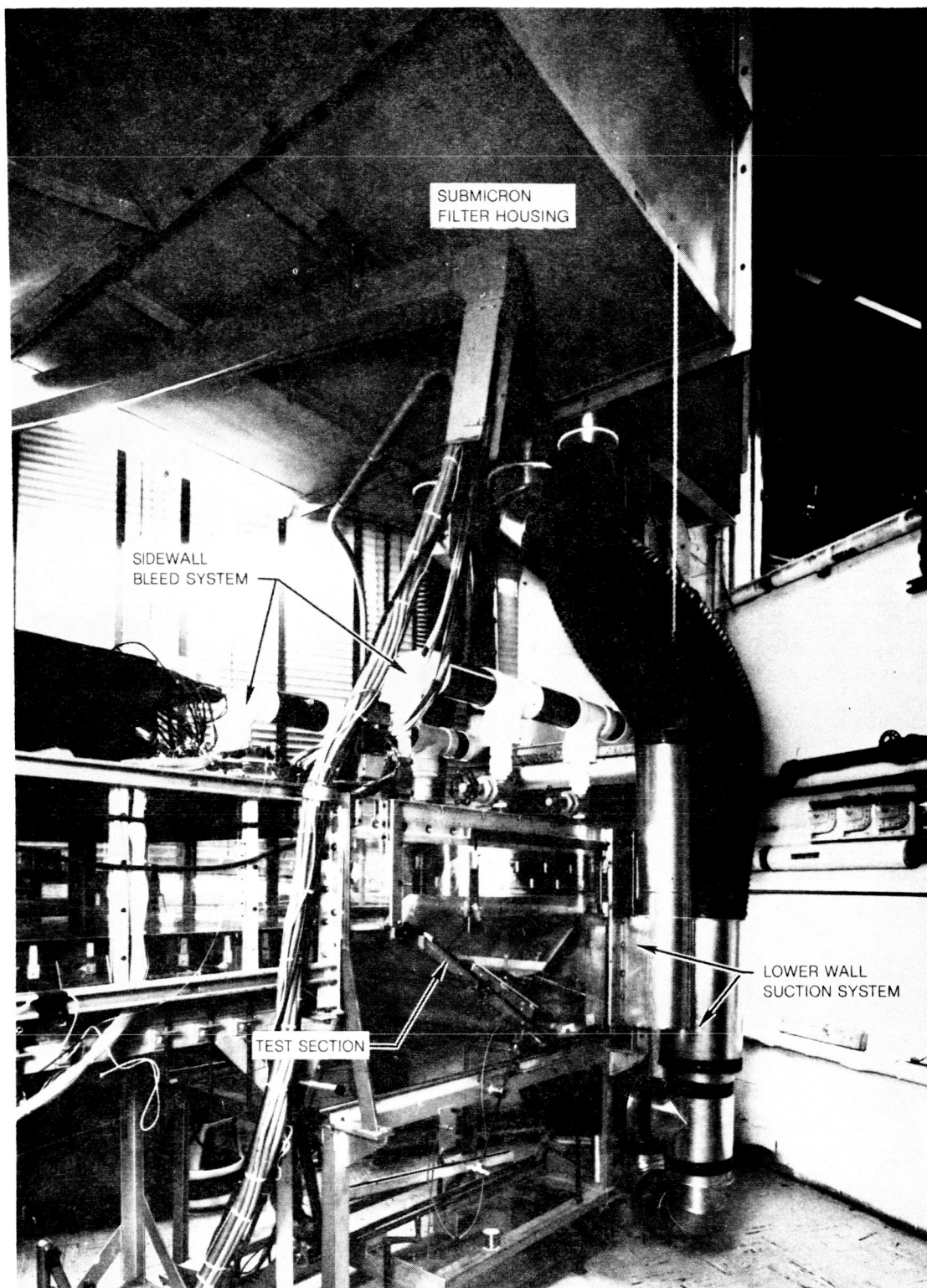


Figure 3-4 Turbulent Separation Bubble Test Section Installed in UTRC Boundary Layer Wind Tunnel

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Figure 3-5 Top of Test Section

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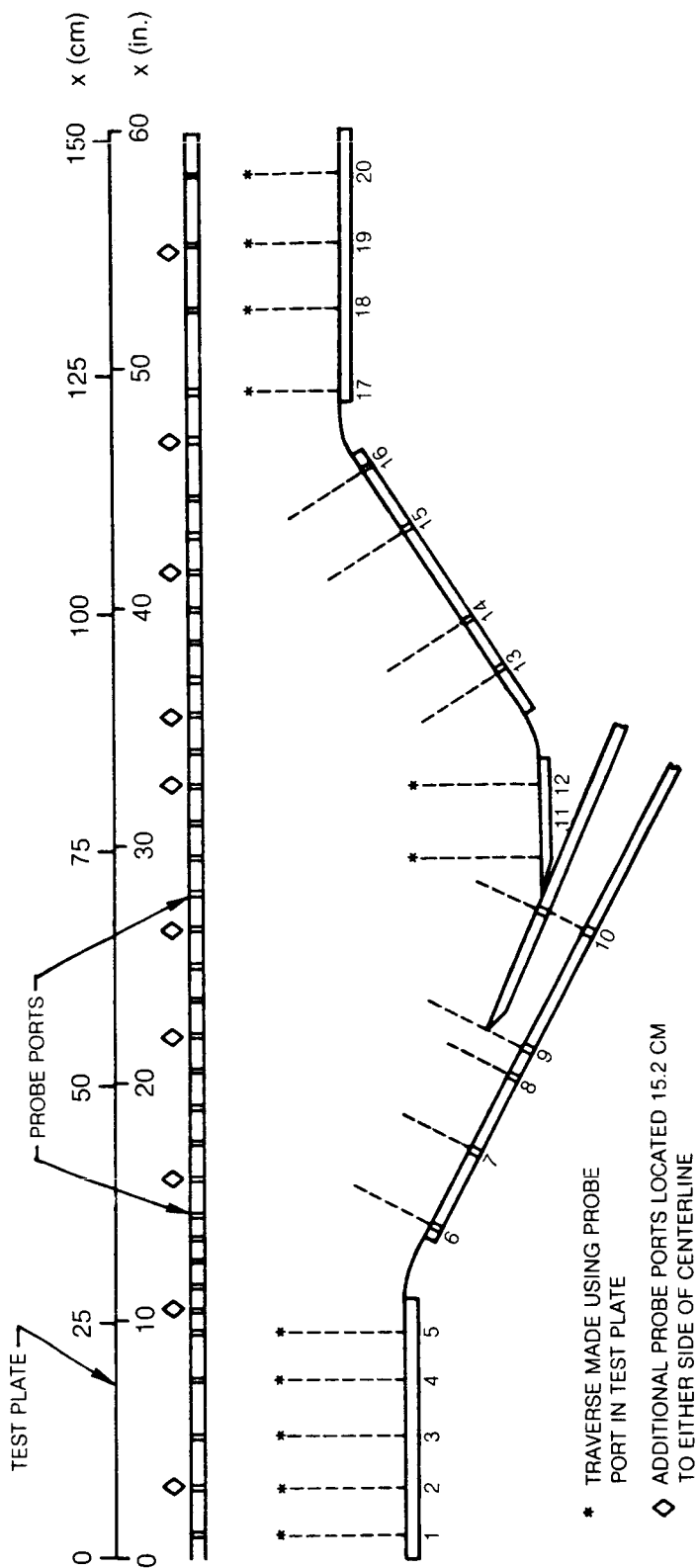


Figure 3-6 Probe Port and Lower Wall Traverse Locations (Test Section Centerline)

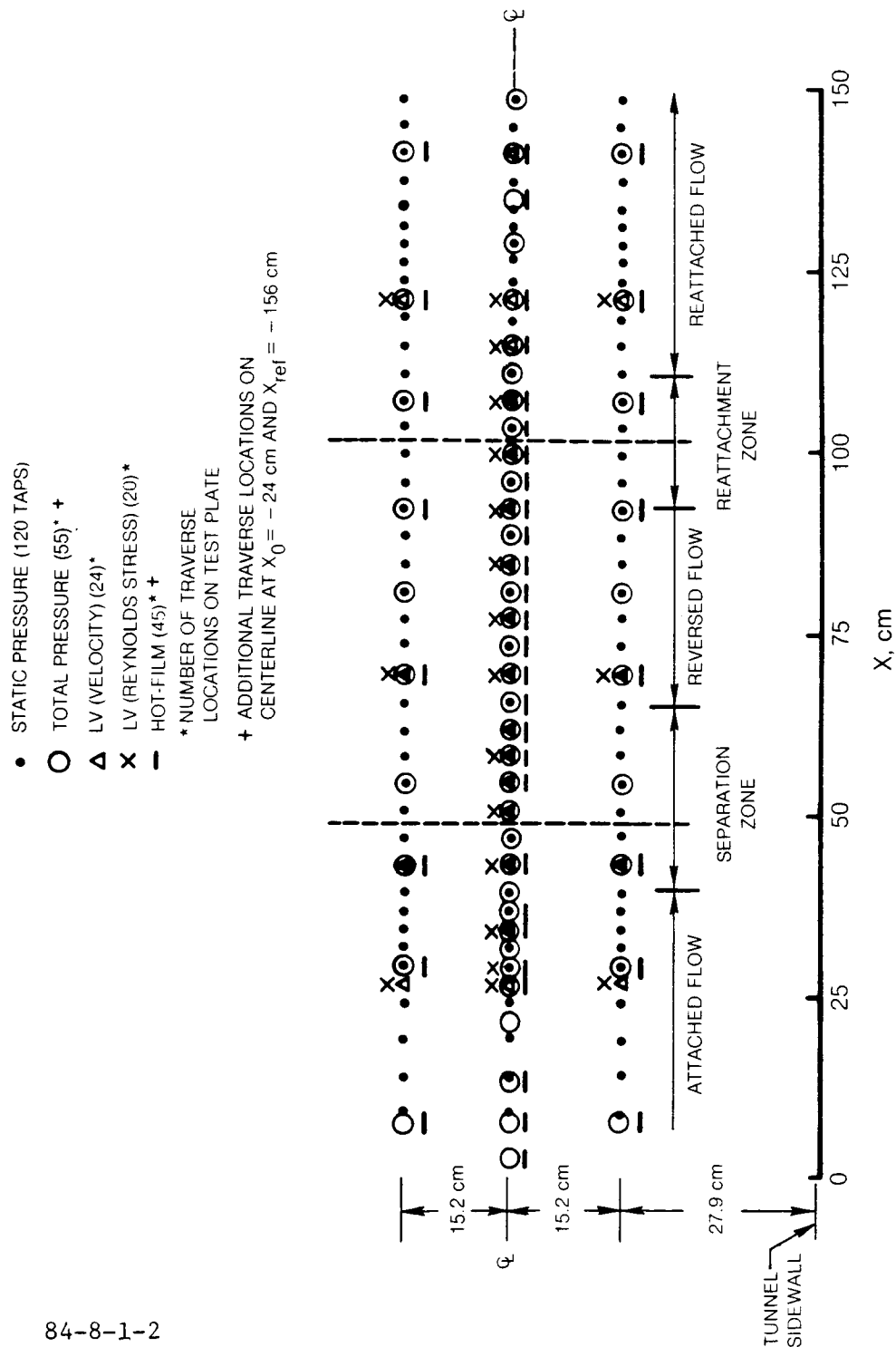


Figure 3-7 Measurement Locations on Test Plate

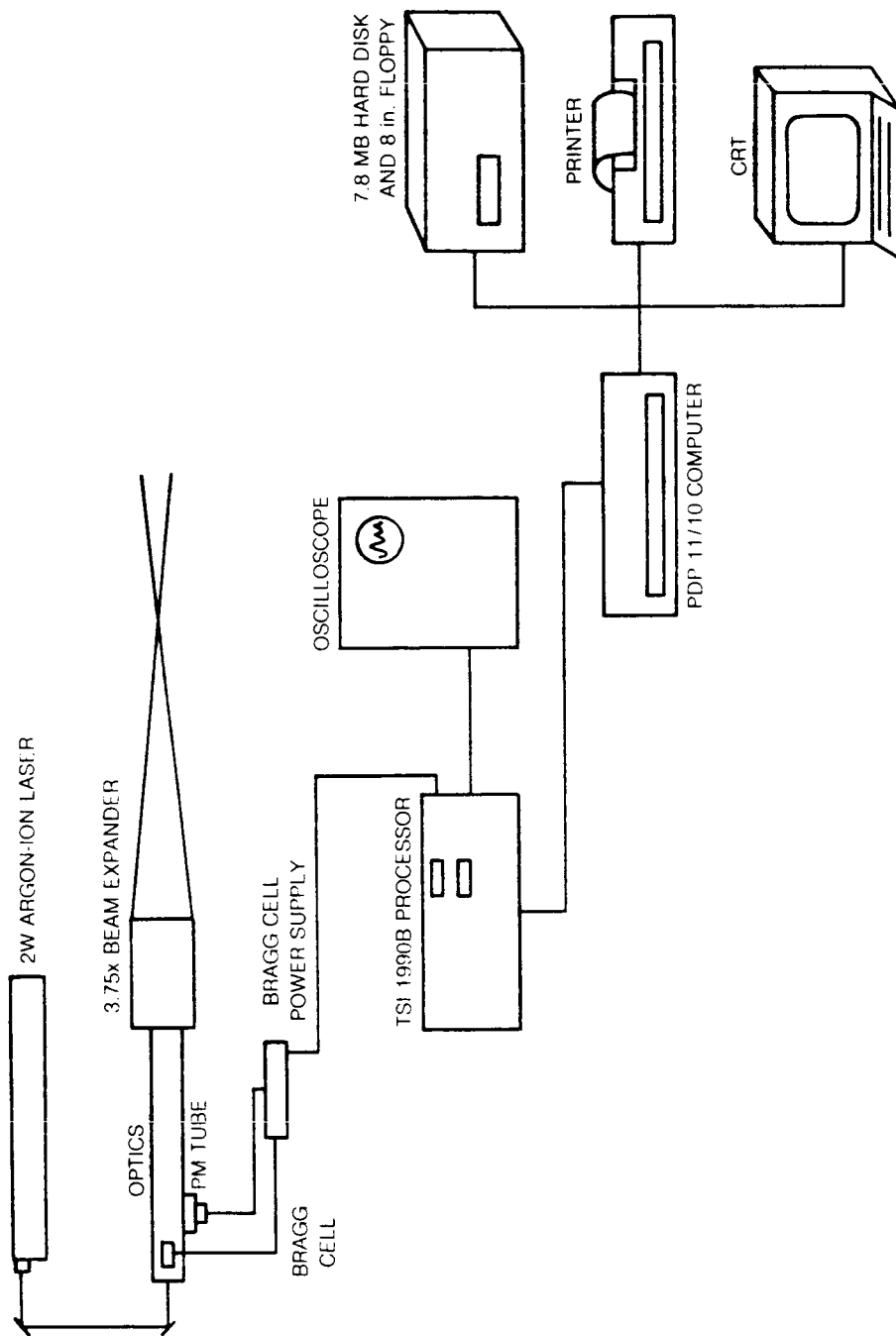


Figure 3-8 Laser Velocimeter Data Acquisition System

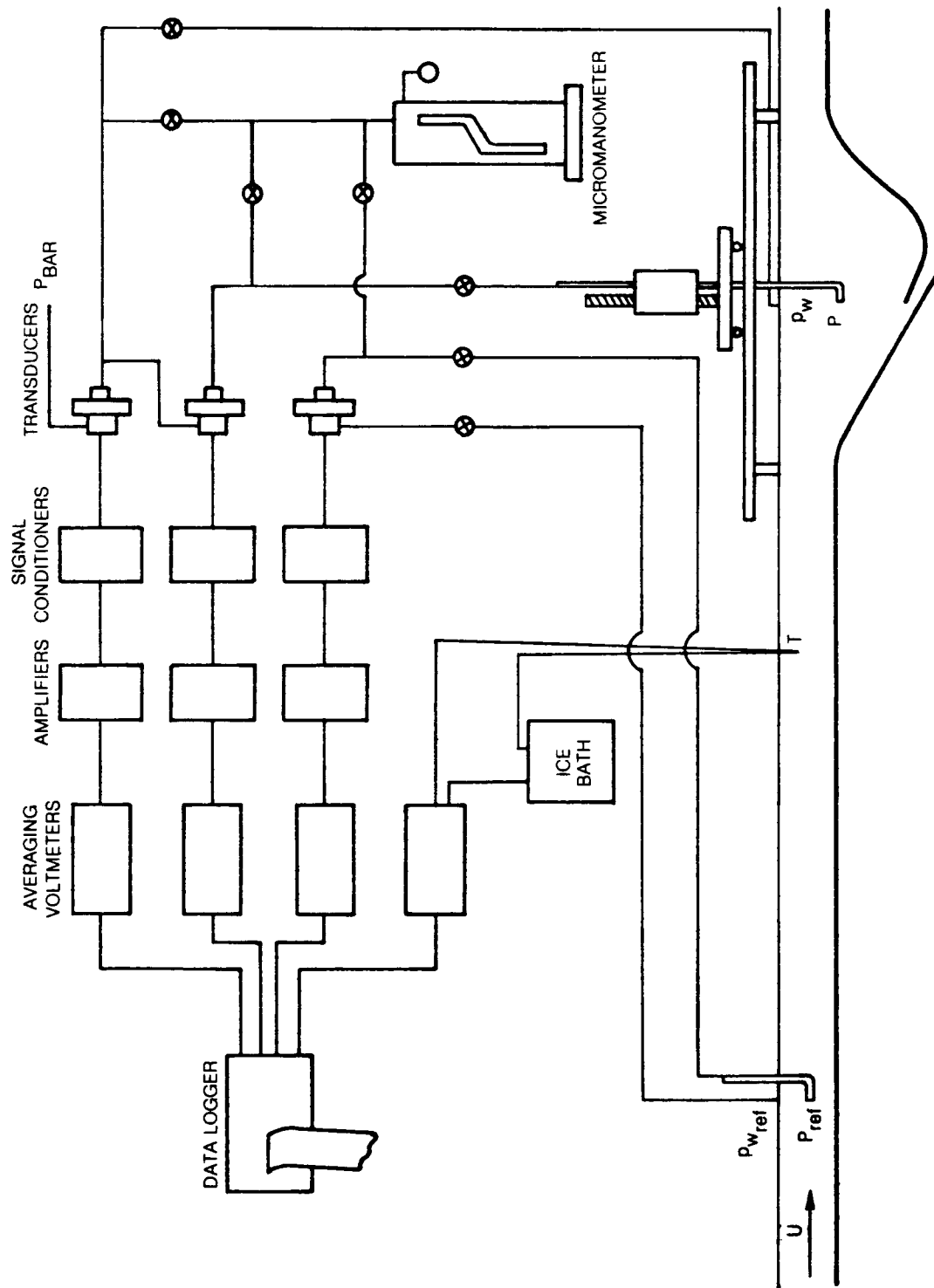


Figure 3-9 Total Pressure Measurement System

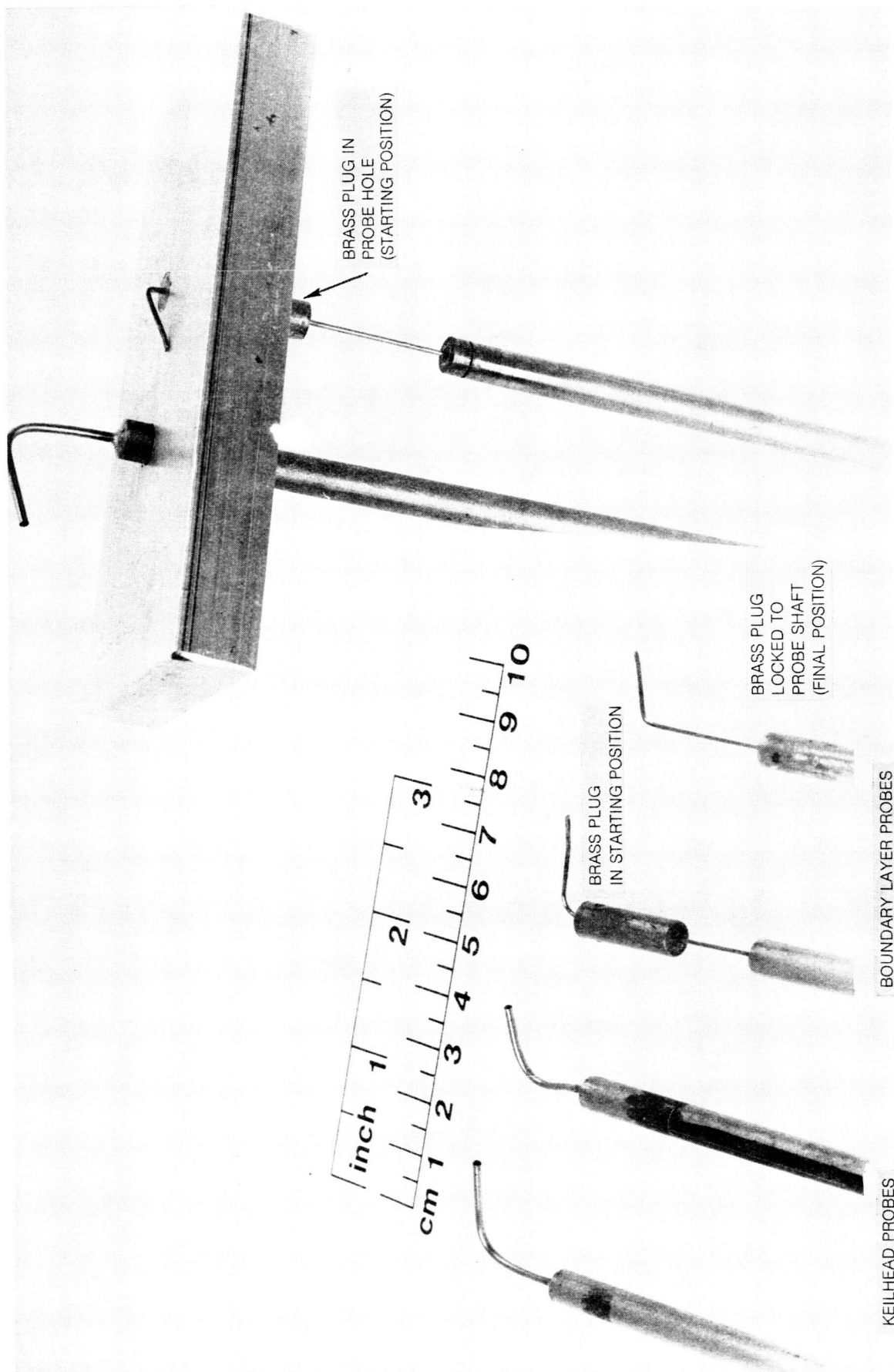


Figure 3-10 Total Pressure Probes

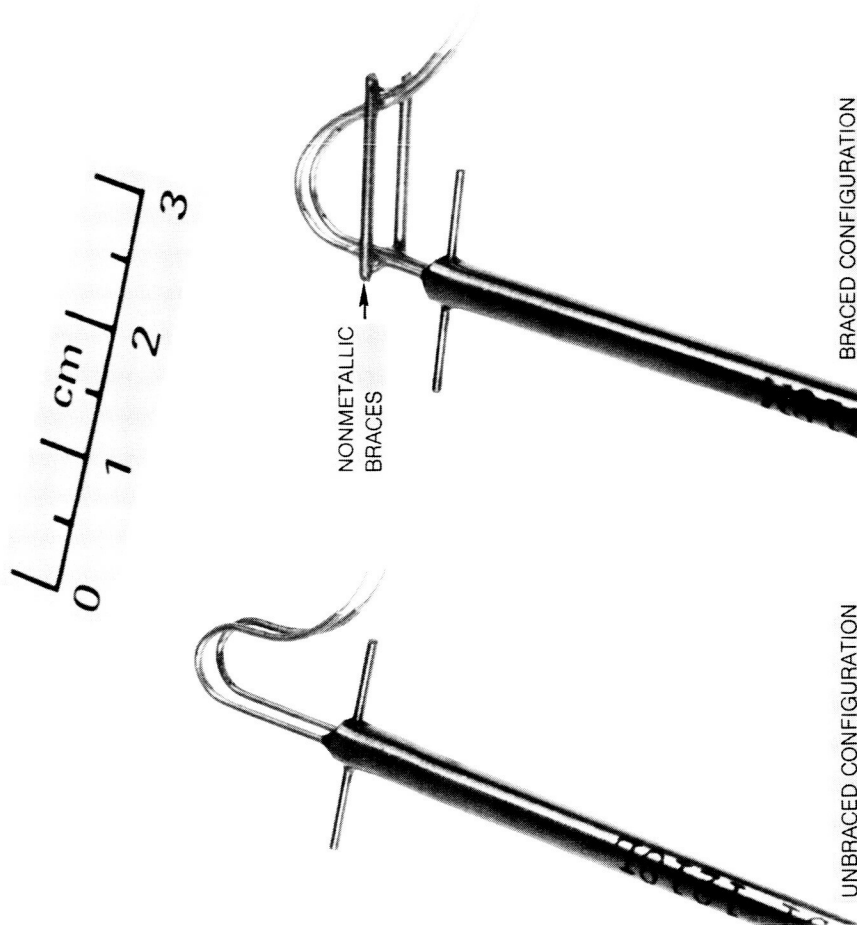
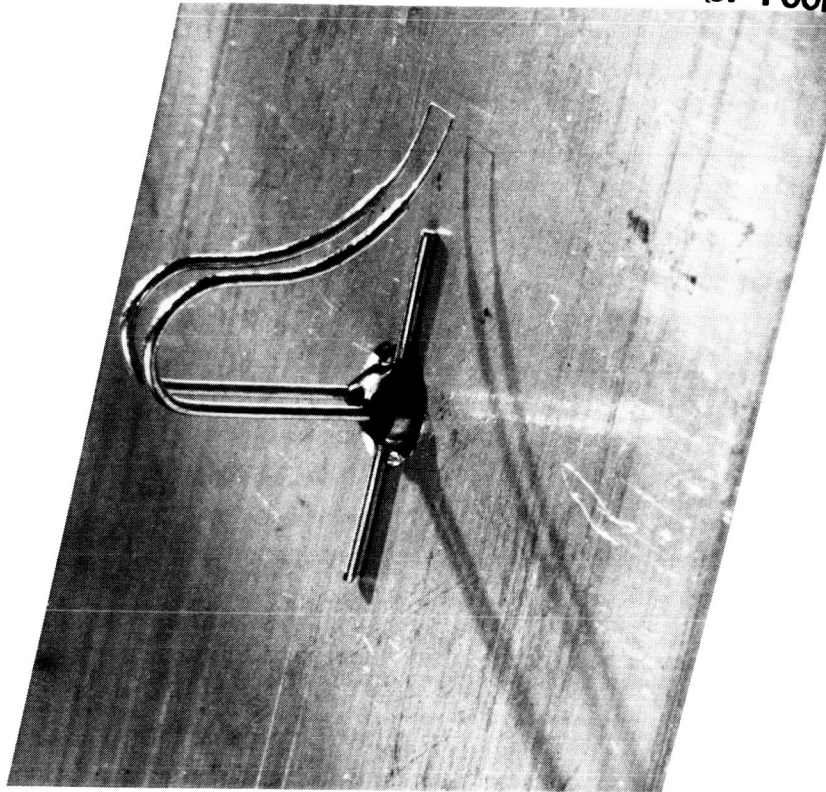


Figure 3-11 Hot-Film Probes

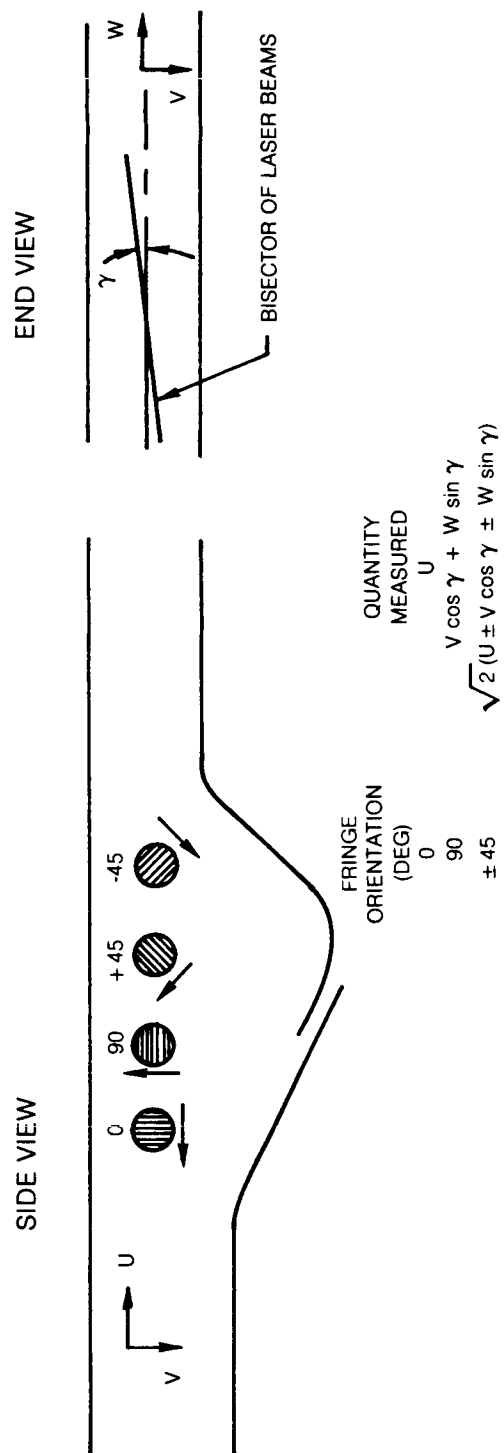


Figure 3-12 LV Measurement Orientations

CHAPTER 4

RESULTS

4.1 Data Presentation

Velocity and pressure data obtained in this study are presented in both tabular and graphical format. Velocity data have been normalized by the free-stream velocity, U_{ref} , at the tunnel reference location ($x = -156$ cm) in the constant velocity approach section upstream of the test section. U_{ref} equaled 27.05 m/sec (88.75 ft/sec) at nominal tunnel operating conditions ($T_{ref} = 22.2^\circ\text{C}$, 72°F and $p_{ref} = 780$ mm Hg, 15.06 psia where p_{ref} was the sum of the tunnel static pressure relative to ambient (18 mm Hg, 10 in H_2O) and the barometric pressure (762 mm Hg)). U_{ref} was adjusted to maintain constant unit Reynolds number at the reference location when tunnel conditions deviated from nominal. Static pressures are referenced to the tunnel static pressure at the reference location. Total pressures were normalized by the freestream dynamic pressure, Q_{ref} , at the reference location. The coordinates used for presentation of results are x , distance downstream from the start of the test section (see figure 3-6), y , transverse distance from the test plate, and z , spanwise position relative to the wind tunnel centerline.

Presentation of the results in the following sections starts with a description of the flow conditions at the initial measurement plane. Then, the results of smoke, tuft, and surface flow visualization are presented to provide an overall understanding of the test section flowfield. Detailed presentations are then made of the test surface static pressure distribution, the mean velocity field, turbulence velocity field, Reynolds stresses, and total pressures throughout the test section.

4.2 Initial Plane Boundary Conditions

To provide data required to start computational codes, an initial measurement plane was chosen well upstream of the region of influence of the adverse pressure gradient and the resulting separated boundary layer. Although such codes should be capable of proceeding downstream from an arbitrary initial profile, the approach geometry for the present study produced a boundary layer having characteristics generally similar to an equilibrium turbulent boundary layer, as discussed below. The initial measurement plane was located in the boundary layer development section 24.1 cm (9.5 in) upstream of the test section inlet. This location, which was 2.5 duct heights upstream of the start of the diverging section, was chosen because test surface static pressure measurements, described subsequently,

showed that the adverse pressure gradient extended less than 1.5 duct heights upstream of the divergence. Pitot probe traverses, both transverse and spanwise, were taken to define the flow uniformity in the initial measurement plane. Hot-film anemometry was used to define profiles of the mean velocity and the axial turbulence component in the test surface boundary layer.

The measured total pressure distribution is shown in figure 4-1. The spanwise pitot traverse taken at the tunnel mid-height showed the total pressure variation to be less than ± 0.5 percent of the dynamic head over the central 90 percent of the span which was outside the sidewall boundary layers. A transverse (vertical) pitot pressure traverse at mid-span was used to define the boundary layers on the test (upper) surface and the lower surface. The boundary layer edge was defined as the location at which the measured total pressure equaled 99 percent of the freestream total pressure (equivalent to δ_{995} determined from velocity measurements). The boundary layer on the test surface, which was tripped at the start of the boundary layer development section (fig. 3-2), measured 7.67 cm (3.02 in) whereas the untripped lower wall boundary layer had a thickness of 3.56 cm (1.4 in), leaving a 9.9 cm (3.9 in) thick inviscid core. Integral properties calculated for the boundary layer on the test surface at the initial measurement plane are tabulated below:

Displacement thickness, $\delta^* = .799$ cm
Momentum thickness, $\theta = .631$ cm
Shape factor, $H = 1.27$
Momentum thickness Reynolds no. = 11,100

The measured shape factor of 1.27 was somewhat less than the value of 1.32 quoted by Coles (ref. 30) for a constant pressure turbulent boundary layer at the measured momentum thickness Reynolds number of 11,100. The velocity profile of the test surface boundary layer was found to be in good agreement with the "law-of-the-wall." In figure 4-2a the profile is plotted in "law-of-the-wall" (U^+ vs. y^+) coordinates. To obtain figure 4-2a the friction velocity, U_τ , was chosen to minimize the least squares fit to the equation

$$U^+ = \frac{U}{U_\tau} = \frac{1}{0.41} \ln y^+ + 5.0 \quad (4-1)$$

where $y^+ = \frac{yU_\tau}{\nu}$ as recommended by Coles (ref. 30) over the log-linear region of the profile ($50 < y^+ < 500$). Then the skin friction coefficient could be calculated from the equation $C_f = 2U_\tau^2/U_{ref}^2$ since $U_\tau^2 = \tau_w/\rho$. Data in the outer region of the boundary layer deviated from the logarithmic portion as

expected. The maximum deviation, ΔU^+ , referred to as the "strength of the wake component" was approximately 1.4. This was less than the value of 2.7 quoted by Coles for an equilibrium turbulent boundary layer having the same momentum thickness Reynolds number.

The measured streamwise turbulence intensity (normalized by boundary layer edge velocity and plotted versus y/δ_{99}) is shown in figure 4-2b to be in good agreement with the turbulence profile presented by Klebanoff (ref. 31) for a flat plate equilibrium turbulent boundary layer. In addition to overall rms measurements, spectra (0-20 KHz) were taken routinely at each hot-film measurement point to ensure that the hot-film signal was free of discrete frequency spikes associated with sensing element vibration.

4.3 Flow Visualization

To optimize the two-dimensionality of the separation bubble, during initial flow visualization testing, surface-mounted tufts and tuft trees (installed in the test section and described previously in Section 3.2) were monitored while adjustments were made to the divergence angle of the lower wall, the boundary layer bleed scoops, and the axial distribution of suction in the test surface sidewall bleed slots. It became apparent that two-dimensionality could only be achieved using a large divergence angle and suction in both the lower wall bleed scoop and the corner bleed slots. This configuration resulted in a long, thick separation bubble having minimal three-dimensionality.

Since the technique of achieving the bubble configurations employed in this experiment may be of interest, some initial exploratory studies will be described. By varying lower wall divergence angle and suction arrangements for the two lower wall slots, a range of bubble configurations could be produced. While the overall bubble length was effectively set by the axial separation of the lower wall divergence and convergence points, bubble thickness could be reduced by decreasing the divergence angle. This tended, however, to produce a more unsteady flow and greater spanwise variation in the separation line. This does not imply that thinner bubbles are inherently more unsteady, rather that a smaller adverse gradient will increase the axial length over which the random process of intermittent separation can occur. The configuration producing the highest degree of bubble two-dimensionality in the present experiment was found to be one in which the divergence angle was increased to the maximum value ($\alpha = 28$ deg) for which slot suction could hold the boundary layer attached to the lower surface. Although the resulting thick bubble caused significant streamline curvature in the x-y plane with resultant transverse static pressure gradients, the strong-adverse-pressure-gradient, strong-suction configuration was considered superior for providing

benchmark quality data for code verification and development compared to a configuration producing a shorter, thinner bubble having unknown three-dimensional contamination.

Tuft flow visualization of the test surface is shown in figure 4-3. The five zones of the separation and reattachment process (attached flow, intermittent separation, reversed flow, the reattachment zone, and reattached flow) are clearly evident to the eye but are obscured somewhat in the photography. The inset, taken from a movie made during flow visualization testing, shows a closeup view of the tufts within the reversed flow region to illustrate the strong reversed flow across the entire tunnel span within the separation bubble. The maximum thickness of the reversed flow region within the separation bubble as indicated by the direction of the tufts on the "tuft trees" which extended from the upper to the lower surface was estimated to be 8 cm (3.1 in). Also indicated by the "tuft trees" is the curvature of the free-stream flow convecting over the separation bubble. Surface mounted tufts on the lower wall confirmed that the boundary layer along the lower wall remained attached throughout the test section.

In figure 4-4 the five zones of separation are depicted more clearly. In the attached flow region all the tufts were steady and pointed downstream. Within the intermittent separation zone, tufts fluctuated in direction between upstream and downstream. In the reversed flow region, tufts in the central 60 percent of the span were steady and pointed upstream. In the reattachment zone, the tufts fluctuated in direction between upstream and downstream as the reattachment point shifted in a random, intermittent manner. In the reattached flow the tufts again pointed downstream but jittered due to high turbulence levels in the wake of the separation bubble.

Photographs of the smoke flow visualization obtained while traversing the single-headed smoke probe vertically at inlet station 0 ($x = -24.1$ cm, -9.5 in) are shown in figure 4-5. For the first photograph (fig. 4-5a) the smoke probe was positioned 10 cm below the test surface ($y_o = 10$ cm) just outside of the 7.67 cm thick boundary layer at the initial measurement plane. The smoke filament flowed smoothly through the test section but was displaced downward by the separation bubble on the test surface. Note that the axial extent of the separation bubble as indicated by tufts mounted on the test surface is marked on the photographs. At $y_o = 7.6$ cm (a location corresponding to the edge of the boundary layer at the initial measurement plane where the smoke was injected) the filament continued to flow smoothly around the bubble (fig. 4-5b), indicating that it was in the low turbulence, inviscid freestream. However, at $y_o = 6.4$ cm (fig. 4-5c) the upper edge of the smoke filament became entrained in the turbulent shear layer surrounding the separation bubble. Near reattachment the smoke filament appears diffuse due to unsteady flapping of the filament lines in that region. When the smoke filament

impinged upon the test surface it was observed that the filament would alternately be ingested into the recirculation region at the aft end of the bubble or be convected downstream. With the smoke probe positioned near the upper wall ($y_0 = 5.1$ cm, fig. 4-5d) the smoke filament became more entrained in the separation bubble. Much of the entrainment occurred in the free shear layer surrounding the bubble as shown in the photograph where a large eddy is being entrained into the bubble in addition to the flow being ingested into the bubble near reattachment. Once within the bubble, the smoke dispersed rapidly causing the smoke density within the bubble to be too low to be seen in the photograph although the smoke was visible as a diffuse haze to the eye.

Flow directions determined from tuft trees, surface tufts, and smoke flow visualization were used to map the streamline pattern throughout the test section (fig. 4-6). The reversed flow region was quite large, being approximately 50 cm long with a maximum thickness of 8 cm. Streamlines upstream of the separation zone were steady and parallel. Near reattachment the streamline pattern for the mean flowfield could only be approximated because of unsteady flapping of the flow-field.

To determine the degree to which a two-dimensional separation had been achieved, tufts were removed from the test section and a low-viscosity red dye was injected through static pressure taps on the test surface (fig. 3-7 shows tap locations). The measurements confirmed the straightness of the separation line indicated by the surface mounted tufts earlier. However, the determination of a quantitative measure of the straightness of the separation line was difficult because the low wall shear in the vicinity of separation barely moved the injected dye. After testing, a sheet of exposed blueprint paper was rolled over the test surface to lift off the dye streaks for permanent storage and subsequent analysis. The dye patterns were interpreted later with the aid of LV measurements of the forward flow fraction (see Section 4.6.1 "Forward Flow Fraction Measurements") at centerline and off-centerline locations near the test surface. Good correlation between a forward flow fraction of 0.5 and lack of motion of the injected dye was obtained. The separation line (i.e. location of transitory detachment) was determined from the dye patterns and interpolation of forward flow fraction data to be straight. The angle of inclination of the straight separation line was 7 degrees with respect to the perpendicular to the tunnel centerline with separation occurring further upstream on the west side of the span ($z > 0$) than the east side ($z < 0$). This 7 degree inclination angle corresponds to a deviation from the line perpendicular to centerline of ± 6 percent of the span which is reasonably close to the ± 5 percent objective.

4.4 Test Surface Static Pressure Distribution

The static pressure distribution on the test surface measured along the tunnel centerline is shown in figure 4-7. The results are presented in the form of a non-dimensional pressure coefficient defined as

$$C_p = \frac{p_w(x) - p_{w1}}{Q_{ref}} \quad (4-2)$$

where $p_w(x)$ is the wall static pressure at any x location, p_{w1} is the wall static pressure measured by the first static pressure tap in the test section ($x = 6.35$ cm) and Q_{ref} is the dynamic pressure. Also shown in the figure are streamlines determined from flow visualization testing and curves estimating the C_p distribution at separation and reattachment based on an analysis by Perry and Fairlie (ref. 5).

The static pressure on the test surface began to rise downstream of the test section inlet ($x > 10$ cm) due to the upstream influence of the 28 deg lower wall divergence which began at $x = 30$ cm and created a strong adverse pressure gradient. At $x = 40$ cm C_p reached a value of 0.36 and the boundary layer separated. The wall static pressure remained constant under the separation bubble except near reattachment where the impingement and partial stagnation of the reattaching flow caused C_p to increase to 0.50 on the test surface. Downstream of reattachment C_p decreased rapidly as the flow accelerated in the converging test section leading to the outlet duct. Near the test section exit C_p approached a constant value of 0.22 due to the net diffusion which occurred in the flow between the inlet and outlet of the test section. As shown in the streamline patterns drawn in figure 4-7, when the flow which was removed from the test section via the lower wall bleed scoop is excluded from consideration, the effective inlet height, h_{in} , of the test section was less than the outlet height, h_{out} , resulting in a net flow diffusion within the test section.

Perry and Fairlie noted that the C_p distribution near separation and reattachment could be approximated by parabolae which were defined by the separation (or reattachment) angle, ϕ , and the nondimensional vorticity, $\hat{\omega}$

$$\tan \phi = \pm 2 \left(- \frac{\partial^2 C_p}{\partial x^2} \right)^{1/2} / \hat{\omega} \quad (4-3)$$

The parabolae shown in figure 4-7 were estimated using measured values of the C_p distribution and separation and reattachment angles estimated from the streamline patterns calculated below from LV data (fig. 5-3). The vorticity was assumed to be constant along the mean dividing streamline and was estimated to be the value which resulted in the best parabolic fit to the measured C_p distribution at reattachment.

Test surface static pressure distributions were also measured at off-centerline locations as one of the diagnostics for establishing the degree of flow two-dimensionality. Results of the off-centerline are tabulated in Table IV beginning on page 192.

4.5 Mean Velocity Field

The velocity field within the test section was measured with a laser velocimeter (LV) and a single-component hot-film probe. The LV measured axial and transverse velocity components separately whereas the hot-film probe measured the magnitude of the velocity vector in the x-y plane. Hot-film measurements were made to provide a degree of redundancy in the measurement of the velocity field and to provide information about the unsteady nature of the flowfield. Additional hot-film measurements were made at stations upstream and downstream of the separation bubble where optical inaccessibility prevented LV measurements. All hot-film data, including data obtained in regions of intermittent flow reversal where the measurements are known to be inaccurate, are presented in Table V. The hot-film velocity data is presented nondimensionally as U_{eff}/U_{ref} and u_{eff}/U_{ref} where U_{eff} and u_{eff} are the mean and rms values of the effective cooling velocity measured by the hot-film probe which was aligned such that the sensor axis was parallel to the z-axis.

Comparison of these data to the more accurate LV data could prove useful in evaluating separation bubble data obtained by other investigators using the hot-wire/film technique. A comparison between hot-film and LV data obtained at selected stations during this test program is presented in Appendix D. Error bounds for the LV measurements determined using the error analysis developed in Appendix C are presented in Table C-5. The complete set of LV data including mean velocity components, turbulence components, forward and transverse flow fractions, and Reynolds stress measurements are presented in Tables II and III. Error bounds for pitot and hot-film measurements are given in Appendix D. The velocity data presented below will consist almost entirely

of LV data except for hot-film data obtained at stations where LV measurements could not be made due to optical inaccessibility.

Velocity vectors determined from LV measurements taken on the wind tunnel centerline have been plotted in figure 4-8 to show the mean flowfield in the test section. Several features of the flowfield are notable. First, the size and location of the separation bubble are in agreement with the flow visualization results. Separation (i.e., $U < 0$ near the wall) occurred at approximately $x = 45$ cm with reattachment (i.e., $U > 0$ at $y > 0$) at $x = 100$ cm resulting in a 55 cm long separation bubble. The strong recirculation within the separation bubble is readily apparent. The maximum thickness of the reversed flow region is almost 9 cm (i.e., slightly larger than the 8 cm thickness indicated from flow visualization) causing a significant displacement and curvature of the freestream flow. Second, near the leading edge of the bubble at $45 \text{ cm} < x < 60 \text{ cm}$, a strong free shear layer is evident between the reversed flow near the surface and the displaced boundary layer. Finally, at $90 \text{ cm} < x < 100 \text{ cm}$, the flow vectors impinge nearly vertically onto the test surface. This impingement caused the peak in the surface static pressure at reattachment which has been discussed in the previous section.

4.5.1 Axial Velocity Measurements

Axial velocity profiles nondimensionalized by U_{ref} are presented in figure 4-9. All data were obtained from LV measurements except the data at Station 1 ($x = 2.54$ cm) which are streamwise velocity components measured with a hot-film probe.

The general mean flow characteristics of the separation-reattachment process are evident in this figure. Retardation of flow near the wall is evident downstream of Station 6 with detachment occurring at Station 13. Within the reversed flow region, shown bounded by a dashed line, peak velocities are observed near the wall although retardation of the reversed flow at the surface is evident in the forward half of the region. Outside of this reversed flow region significant (apparent) profile adjustments are observed over the axial extent of the reversed flow zone. Downstream of Station 26 reattachment occurs with the development of a new boundary layer downstream suggested by the near-wall data points.

More detailed axial velocity profiles are presented in figures 4-10 a-d. In these figures the axial velocity profiles are plotted in the non-dimensional form U/U_e vs. y/δ where U_e is the local boundary layer edge velocity at $y = \delta$ determined from laser velocimeter measurements and δ is the local boundary layer thickness determined from total pressure traverses as described below in Section 4.9. The data are plotted using semilogarithmic coordinates near the wall ($y/\delta < 0.1$) and linear coordinates outside the near-wall region to permit the closely spaced data points in the near-wall region

to be presented clearly. The profiles are also displaced for clarity. Symbols adjacent to left and right borders show individual profile ordinates of zero and 1.0, respectively. By comparing the profiles in part (a) to the zero values the retardation of the near wall layer between Stations 0 and 11 is evident. Part (b) of the figure shows that at Station 13 a maximum reversed flow velocity of $0.10 U_e$ ($0.075 U_{ref}$) has been measured. The maximum reversed flow velocity at each station increases monotonically with distance downstream until Station 22 (located approximately $2/3$ of the bubble length aft of the detachment location) where a value of $0.397 U_e$ ($0.202 U_{ref}$) is reached. As shown in part (d) of the figure, reattachment and the resumption of downstream flow occurs between Stations 26 and 28. At Stations 15 through 24 values of U/U_e greater than unity were measured within the boundary layer ($y/\delta < 1$). These results, caused by normal static pressure gradients produced by flow curvature in the test section, are analyzed in Sec. 5.3.2.

4.5.2 Transverse Velocity Measurements

Nondimensional transverse velocity profiles, y/δ vs V/U_{ref} , obtained from LV measurements are presented in figures 4-11 a-c. Positive transverse velocities correspond to flow away from the test surface. Figures 4-11a and 4-11b show that at Stations 6 through 16 in the upstream half of the test section, the transverse velocity, V , increases monotonically with y/δ as the flow moves away from the test surface. Positive transverse velocities within the reversed flow region are consistent with the expected counter clockwise bubble recirculation pattern. Downstream of Station 16 the transverse velocity component decreases to a value near zero at Station 20. Downstream of Station 20 negative transverse velocity components are measured indicating flow toward the test surface. As shown in figure 4-11b and 4-11c the components exceed 40 percent of U_{ref} in the reattachment zone located in the vicinity of Stations 28 and 30. At Station 34 in the exit duct the transverse component magnitude has decreased to the 0-5 percent range.

In summary, the measurements show that significant transverse velocity component magnitudes occur within the boundary layer regions defined by total pressure measurements. As in the case of the axial velocity measurements, profile alterations with increasing axial distance are observed to be significant.

4.6 Intermittency Measurements

The directionally sensitive laser velocimeter was used to measure the fraction of the time the flow was moving in the downstream direction ($U > 0$) and the fraction of the time the flow was moving away from the test surface ($V > 0$). Simpson et al (ref. 1) have referred to the former measurement as

the intermittency and/or the forward flow fraction. In this report the latter terminology will be adopted and "transverse flow fraction" will be used to denote the fraction of the time the flow moved away from the test surface. In practice these quantities were determined from the ratio of the number of valid samples having positive velocities to the total number of valid samples comprising each LV measurement.

4.6.1 Forward Flow Fraction Measurements

Figure 4-12 shows the distribution of the forward flow fraction throughout the test section. Corresponding tabular information is provided in Table 2. Upstream of separation (Stations 5 and 8) the flow fraction was unity across the entire profile indicating that the flow was moving in the downstream direction 100 percent of the time. The first indication of intermittent reversed flow occurred near the test surface at Station 11 where γ_{p_U} first deviated from 1.0. Further downstream the backflow region intensified and spread outwards from the test surface. At Stations 18 through 22, a strong steady reversed flow ($\gamma_{p_U} = 0$) extended several centimeters from the test surface. The region of the flow in which reversed flow existed for some fraction of time ($\gamma_{p_U} < 1$) extended more than 17 cm from the test surface. Notice also that the locus of points at which $\gamma_{p_U} = 0.50$ corresponded closely to the boundary of the reversed flow region. The correspondence would be exact if the LV probability distributions were symmetric with respect to $U = 0$. However, near the edge of the reversed flow region, the velocity histograms were skewed because of the nature of the flow. Since the maximum backflow velocity was much less than the freestream velocity, the probability of a turbulent fluctuation having a large positive velocity was greater than the probability of it having a large negative velocity causing a skewed histogram.

More details of the development of the separated flow can be seen in figure 4-13 in which the forward flow fraction is plotted versus y/δ in log-linear coordinates for stations within and adjacent to the separation bubble. As noted above, occurrences of reversed flow appeared initially at Station 11 near the test surface. Downstream of Station 11 these occurrences became more frequent (γ_{p_U} decreased) and penetrated further into the viscous layer as defined by the local boundary layer thickness, δ . At Stations 15 and 16 the forward flow fraction distribution formed a trough near the wall with the more intense regions of reversed flow located slightly away from the test surface ($0.01 < y/\delta < 0.05$).

Downstream of Station 16 the trough-shape disappeared as strong, steady reversed flow was measured adjacent to the test surface at Stations 18 through 22 over almost 10 percent of the boundary layer thickness. These data are

consistent with the velocity profile data shown in figure 4-10 which showed the most intense reversed flow which exceeded 30 percent of the local boundary layer edge velocity occurred at Stations 18, 20 and 22.

Near reattachment, trough-shaped patterns reappeared as the reverse flow weakened. The first reoccurrence of forward flow near the test surface at the reference near-wall measurement location (i.e. $y = 0.10$ cm) appeared at Station 24 where $\gamma_{p_U} = 0.012$ at $y/\delta = 0.0034$. The near-wall forward flow fraction increased to 0.144 at $y/\delta = 0.0042$ and 0.714 at $y/\delta = 0.0050$ at Stations 26 and 28, respectively. At Station 30 the reattachment process was completed and a steady flow profile was reestablished. The axial extent of the reattachment zone from the occurrence of forward flow ($\gamma_{p_U} > 0$) to $\gamma_{p_U} = 0.50$ near the wall (i.e. $C_f \approx 0$) has been determined by data interpolation to be approximately 12 cm. The complete reattachment zone extended from Station 24 to Station 30, a distance of 22.8 cm. For comparison, the boundary layer thickness at Station 8 just upstream of separation was 11 cm. A final point which should be noted in figure 4-13 is the absence of occurrences of reversed flow in the outer 40 percent of the boundary layer at any measurement station.

The trough-shaped pattern noted near separation was similar to the flow fraction distribution measured by Simpson et al (ref. 2) at the downstream stations in their turbulent separation experiment. They did not achieve steady reversed flow ($\gamma_{p_U} = 0$) anywhere in their test section. The minimum forward flow fraction which they measured, $\gamma_{p_U} = 0.05$, occurred at $y/\delta = 0.023$ at their final measurement station. Thus, the open separation bubble data of Simpson et al. would not be expected to correlate well with closed separation bubble data obtained downstream of the leading edge of the bubble.

4.6.2 Transverse Flow Fraction Measurements

The distribution of the transverse flow fraction throughout the test section is shown in figure 4-14. The transverse flow fraction data are consistent with the mean LV flow directions presented above (fig. 4-8). Near the test surface $\gamma_{p_V} \approx 0.50$ except at Stations 28 through 31 where the mean flow impinged strongly onto the test surface. The transverse flow fraction value of 0.5 occurs when the mean flow vector is approximately parallel to the test surface since transverse turbulence fluctuations cause the flow to have an equal probability of moving toward or away from the test surface.

The direction of the freestream flow as indicated by the transverse flow fraction is also consistent with the LV velocity data. In the upstream half of the test section (Stations 6-18) the freestream flow moved away from

the test surface 100 percent of the time ($\gamma_{p_v} = 1$). In the downstream half of the test section (Stations 22-31) the freestream flow moved toward the test surface 100 percent of the time ($\gamma_{p_v} = 0$).

4.7 Unsteady Flowfield

Flow visualization had shown the flowfield in and around the separation bubble to be unsteady. Much of the unsteadiness, such as the streamline flapping at reattachment and the oscillation of the separation line, seemed to be of large scale and occurred at low frequency. It was not clear from flow visualization whether such large scale fluctuations were random (i.e. low frequency turbulence) or ordered (i.e. periodic unsteadiness). In addition, to random versus periodic considerations, the question of whether fluctuations should be considered "turbulence" or "flow unsteadiness" is important to developers of computational procedures. This arises because measured unsteadiness levels can be interpreted in terms of turbulence level (and hence effect turbulence modeling) or interpreted as an unsteady flow with lower levels of imbedded turbulence.

To obtain some information regarding the nature of the unsteadiness in the flowfield, the frequency content of the flow was measured with a hot-film probe during traverses at three critical regions of the flowfield. Frequency data were obtained at Station 13 in the intermittent separation zone, at Station 18 within the reversed flow region, and at Station 28 in the reattachment zone. Typical spectra of the hot-film signal taken over the 0-500 Hz range are shown in figure 4-15. Except for a single discrete frequency spike in the spectrum obtained in the freestream ($y = 27$ cm) at Station 18, all spectra were broadband indicating random unsteadiness. The single low amplitude spike at 460 Hz was caused by blower noise generated at the blade passing frequency. Additional 0-20 KHz spectra taken during each hot-film measurement to check for probe vibrations revealed no flow periodicity at high frequencies.

4.7.1 Streamwise Turbulence Measurements

The broadband spectra showed considerable strength in the low frequency range ($f < 50$ Hz). To quantify this low frequency contribution to the turbulence signal, two rms measurements of the linearized hot-film signal were made. For the first rms average, which was performed for each hot-film measurement made in the test program, the prefilters on the rms voltmeter were set to average the signal over the wideband range of 5 Hz-50 KHz. In addition, the voltages obtained at Stations 13, 18, and 28 were averaged on a

second voltmeter to permit determination of the rms contribution in the low frequency 5-50 Hz range.

Turbulence intensity profiles (y vs. $\sqrt{u_{eff}^2}/U_{ref}$) calculated from the rms voltage averaged over the 5 Hz-50 KHz bandwidth are shown in figure 4-16 as solid lines. The mean square turbulence level $\overline{u_{eff}^2}$ can be considered the turbulence level in the x-y plane associated with the local mean flow direction. Note that the turbulence intensities have been normalized by U_{ref} rather than U_e to provide absolute rather than relative turbulence intensities. Upstream of separation the flow had a standard Klebanoff-like turbulence profile as shown previously. High turbulence levels exceeding 20 percent were measured in the free shear layer surrounding the separation bubble. These peak turbulence levels decayed somewhat downstream of reattachment but remained above 10 percent at the test section outlet.

At Stations 13, 18, and 28 the portion of the overall streamwise turbulence level attributed to the low frequency (5 Hz-50 Hz) band has been shaded. This low frequency contribution to the overall turbulence level was substantial across the entire profile. In the free shear layer the low frequency (5 Hz-50 Hz) unsteadiness accounts for approximately 40-45 percent of the overall turbulence level (5 Hz-50 KHz). Uncertainty in these measurements exists within regions of flow reversal.

Turbulence data at Stations 13, 18, and 28 are listed in Table V. Measurement points where flow reversal occurs some fraction of the time ($0 < \gamma_{p_u} < 1$) are indicated in the table. At those points the rms average of the hot-film voltage does not yield an accurate measurement of the turbulence level (see Appendix D). Thus, care should be taken when using the data in Table V.

With regard to the issue raised above regarding interpretation of measured unsteadiness as turbulence or a basically unsteady flow with imbedded turbulence, the above measurements were not definitive. Some form of conditional sampling may be required to address this issue more directly. That large scale turbulence with low frequency content existed within and in the vicinity of the recirculation zone is clear based on the smoke flow visualization movie taken as part of the study. Overall flowfield unsteadiness was also apparent. This was particularly noticeable in the aft end of the bubble where a previously described non-periodic flapping of the reattaching flow occurred. This flapping phenomenon has been reported previously by Eaton and Johnston (ref. 32), for a reattaching backward-facing step flow, Cherry et al. (ref. 33), for a separating and reattaching flow at the leading edge of a two-dimensional rectangular blunt plate, and Mabey (ref. 34) among others. Mabey

showed that reduced shedding frequencies from various experiments correlated well when normalized by the reattachment length. He suggested that a feedback mechanism, whereby the shedding of vorticity from reattachment interacted with the formation of disturbances near separation, controlled the separation process. In the present experiment a characteristic disturbance length can be estimated from the flapping frequency, $f < 50$ Hz, and the average freestream velocity in the vicinity of the bubble, $U_e = 15$ m/sec, to be greater than 0.3 m (i.e. half the length of the separation bubble).

An additional degree of unsteadiness would be expected in the current experiment because of the intermittent nature of turbulent boundary layer separation on a flat plate. The random upstream and downstream wandering of the separation line due to the lack of a salient edge to fix the location of separation presumably added to the downstream unsteadiness. Thus, there is sufficient evidence to conclude that the unsteadiness observed was not an artifact of the wind tunnel test configuration employed here.

4.7.2 LV Turbulence Measurements

Accurate measurements of the turbulence levels throughout the test section, including regions of flow reversal, were made with the laser velocimeter. An overview of the axial and transverse turbulence intensity profiles determined from LV data is shown in figure 4-17. Qualitatively, the axial turbulence intensity profiles are similar to the streamwise turbulence intensity profiles from hot-film measurements presented in figure 4-16. The transverse turbulence intensity profiles have the same general characteristics as the axial turbulence profiles although lower in level. Peak transverse turbulence intensities were approximately 12 percent while the corresponding peak axial turbulence intensities exceeded 20 percent.

4.7.2.1 Axial Component Turbulence Measurements

More detailed axial turbulence intensity profiles are shown in figures 4-18 a-d where the data are plotted in nondimensional coordinates, y/δ vs. $\sqrt{u^2}/U_{ref}$. At Station 0, located 24 cm upstream of the test section, the boundary layer had a Klebanoff-like turbulence distribution with maximum turbulence intensity of approximately 8 percent as noted previously. As the flow moved downstream and approached separation, turbulence levels near the test surface increased rapidly. At Station 11, the start of intermittent separation, turbulence reached a level of 17 percent at $y/\delta = 0.10$. Just downstream of the mean separation location (Station 13) peaks in the turbulence intensity profiles grew higher and wider, and moved away from the test surface due to turbulence being generated in the free shear layer and diffusing throughout the boundary layer. The peak turbulence intensity of 21

percent was measured at Station 15 at $y/\delta = 0.34$. Downstream of Station 15 the peaks in the profiles decayed, continued to widen, and shifted outwards to larger values of y/δ . Over the upstream half of the separation bubble the peak turbulence intensity occurred approximately 0.1δ farther from the test surface than the mean dividing streamline (see Table VI, Streamline No. 1 for coordinates of the mean dividing streamline determined from LV measurements). Over the downstream half of the separation bubble the peak turbulence intensity shifted further outside of the mean dividing streamline.

At all stations the axial turbulence intensity in the freestream approached 2 percent or less except at Station 34 at the test section outlet where upper and lower wall boundary layers began to merge causing the freestream turbulence level to rise to 4 percent. The freestream turbulence level of 2 percent is a quantitative measure of the overall unsteadiness of the freestream flow in the test section.

4.7.2.2 Transverse Component Turbulence Measurements

Detailed nondimensional transverse turbulence profiles are shown in figure 4-19 a-d. At initial measurement Station 6 the turbulence distribution for this component again exhibited a standard Klebanoff-like profile with a maximum intensity of approximately 4 percent. Approaching separation, transverse turbulence levels increased near the test surface. At the leading edge of the separation bubble the transverse turbulence level peaked at 8.2 percent at $y/\delta = .17$. Just downstream of separation at Stations 14 through 16 the peak transverse turbulence level remained constant at approximately 8 percent but widened and diffused outward from the test surface.

The behavior of the transverse turbulence intensity at the next several measurement stations provides insight into the nature of the transverse velocity fluctuations. At Station 18 the transverse turbulence intensity peaked at 12.6 percent. The peak declined to 9.6 percent at Station 20 before increasing to 11.8, 12.6, and 12.7 percent at Stations 22, 24, and 26, respectively. The mean transverse velocity profiles plotted in figure 4-11b indicated positive transverse velocities at Station 18, negligible transverse velocities at Station 20, and negative transverse velocities at Stations 22, 24, and 26. Thus it seems possible that a major contribution to transverse turbulence intensities originate as streamwise velocity fluctuations when the mean streamline had a nonaxial orientation.

The high transverse turbulence levels at Stations 26, 28 and 30 near reattachment also resulted from unsteady streamline flapping. Downstream of reattachment transverse turbulence intensity decreased due to turbulence decay and a more axial orientation of the streamwise flow vector. Transverse

turbulence levels in the freestream approached 2 percent or less at all stations.

4.7.3 Turbulence Kinetic Energy

The turbulence kinetic energy per unit mass, k , is defined as

$$k = (\overline{u^2} + \overline{v^2} + \overline{w^2})/2 \quad (4-4)$$

Although the spanwise turbulence component, w , was not measured in this experimental program, Simpson (ref. 4) has shown that in separated flows $v \approx w$. Thus, k can be approximated as

$$k = (\overline{u^2} + 2 \overline{v^2})/2 \quad (4-5)$$

Turbulence kinetic energy profiles calculated using eq. (4-5) are presented in figure 4-20. The profile shapes are somewhat similar to the axial turbulence profiles discussed above. The profiles had sharp and growing peaks near separation (Stations 11-13), remained at nearly constant peak amplitude but broadened near the maximum bubble thickness (Station 18-22), and decayed downstream of reattachment. The profile peaks occurred just outside the location of the mean dividing streamline over the upstream half of the bubble, whereas downstream of the maximum bubble thickness, they moved outward from the mean dividing streamline into the bubble wake.

4.8 Reynolds Stress Measurements

Profiles of the Reynolds stress, \overline{uv} , were measured with the LV system at 20 stations. Fourteen of the stations were located on the wind tunnel centerline and six were located at ± 15.2 cm on either side of the centerline at three axial locations (upstream of the separation bubble, within the bubble, and downstream of reattachment). Reynolds stress data from thirteen centerline locations is listed in Table III. Profiles obtained at twelve stations along the wind tunnel centerline are plotted in figure 4-21. Five features of the Reynolds stress profiles should be noted. First, at Station 6 the Reynolds stress has a Klebanoff-like profile (fig. 18.5 in ref. 35). Second, in the freestream flow around the bubble the Reynolds stress is negligible as expected. Third, the Reynolds stress peaks near reattachment and remains high downstream of reattachment. Fourth, the Reynolds stress is small in the reversed flow region. And fifth, just upstream of separation and

in the shear layer surrounding the bubble no meaningful trend is apparent in the Reynolds stress data.

The almost random nature of the Reynolds stress profiles in the separated flow region is not particularly elucidative. However, the Reynolds stress data in this coordinate system can be used to calculate shear stress profiles in a coordinate system aligned with the local mean flow direction. This streamwise shear stress is more meaningful for developing flow structure models, since the assumptions used in the boundary layer equations which are used to calculate separating flows are more accurate if applied in streamwise orthogonal coordinates (ref. 6). It will be shown below in Section 5.7, "Streamwise Turbulent Shear Stress Measurements" that the large values of shear stress expected in the shear layer are masked by the effects of flow curvature and they do not become fully apparent until the streamwise shear stress is calculated.

4.9 Total Pressure Measurements

Total pressure traverses were made normal to the test surface at 55 stations. Thirty-five stations were located on the wind tunnel centerline and twenty traverses were made at off-centerline locations as shown in figure 3-7. The total pressure measurements obtained at each centerline traverse location and at fourteen off-centerline locations are listed in Table IV.

The total pressure profiles obtained on the wind tunnel centerline are shown in figure 4-22. For clarity, only 18 of the 34 profiles have been plotted. The measured total pressure has been normalized by Q_{ref} , the free-stream dynamic pressure at the inlet station ($x = -9.5$ in, -24.1 cm). Several features of the total pressure profiles are apparent.

The inviscid core, defined as the region over which $0.99 < P/Q_{ref} < 1.00$, which is approximately 10 cm thick upstream of the location of intermittent separation ($x < 40$ cm), remained intact as it was convected around the bubble. In the outlet channel ($x > 120$ cm) the thickness of the inviscid core diminished but did not disappear until the last measurement station ($x = 148$ cm) where the upper and lower wall boundary layers merged.

The deceleration of the test surface boundary layer in the region $0 < x < 40$ cm is also apparent. The shape of the boundary layer profile changed as the flow encountered the adverse pressure gradient until an inflection point was measured in the profile at the wall at $x = 40.6$ cm just upstream of separation.

Within the reversed flow region $\partial p / \partial y \approx 0$ except very near the test surface where a reversed flow boundary layer developed under the separation bubble. The presence of the reversed flow boundary layer is not apparent in figure 4-22 but it can be discerned in the tabulated data in Table IV and it is discussed in detail below in Section 5.5.1, "Description of the Backflow Boundary Layer".

Downstream of reattachment a new boundary layer began to grow along the test surface beneath the remnants of the upstream boundary layer which had been convected around the separation bubble. Details of the boundary layer downstream of reattachment are discussed in Section 5.6, "Description of the Reattachment Process".

4.9.1 Determination of Bounding Streamline

Total pressure traverses were made normal to the lower wall of the test section at 20 locations on the wind tunnel centerline to determine the location of a free streamline required as a boundary condition for numerical computation codes. Using wall static pressures measured at each of the 20 traverse locations and assuming that no normal static pressure gradients existed between the lower wall and the location of the bounding streamline, mass flow profiles were calculated from the measured total pressure profiles at each of the 20 axial stations. After accounting for the mass flow out of the lower wall boundary layer scoop, points of equal mass flux were connected to define the bounding streamline shown in figure 4-23.

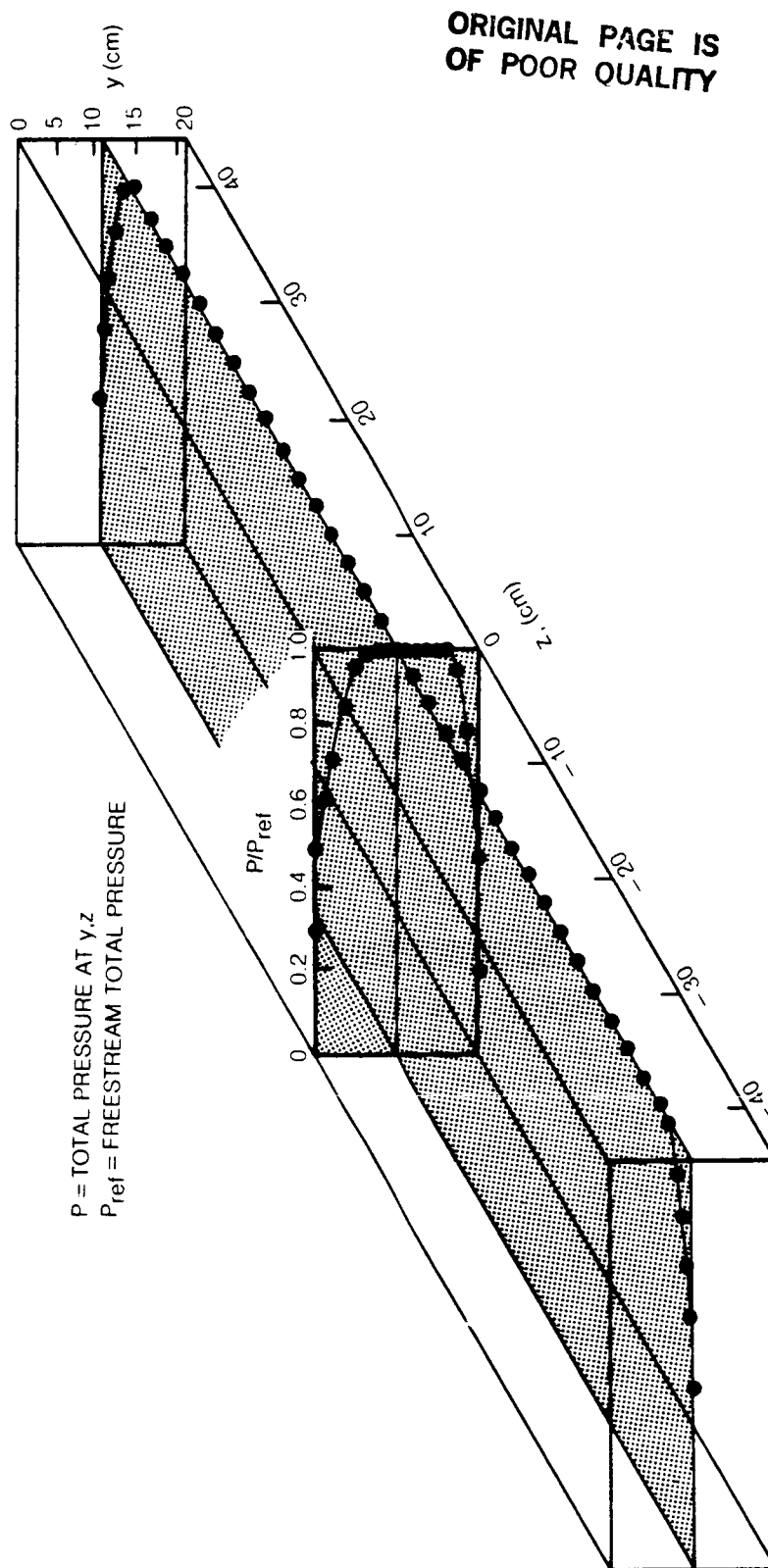
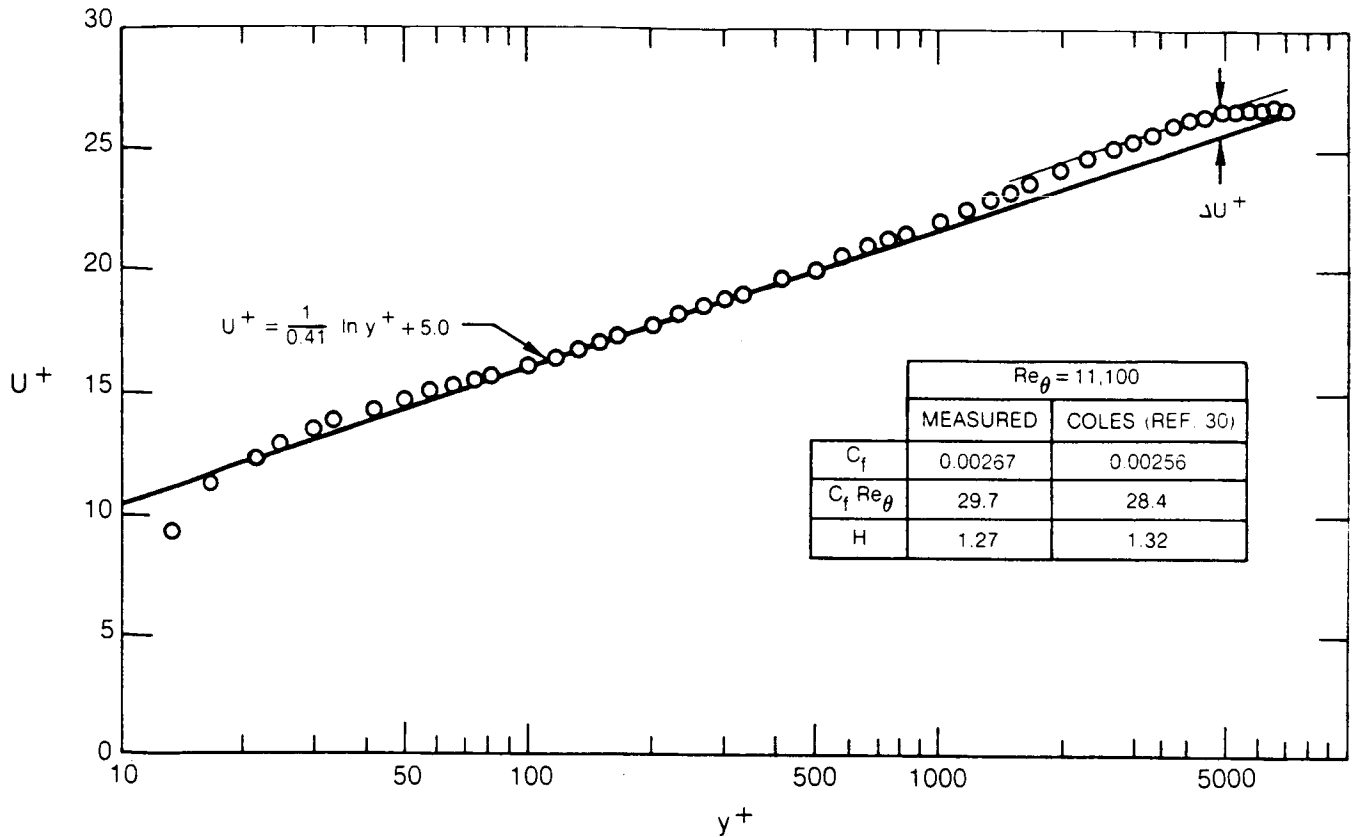
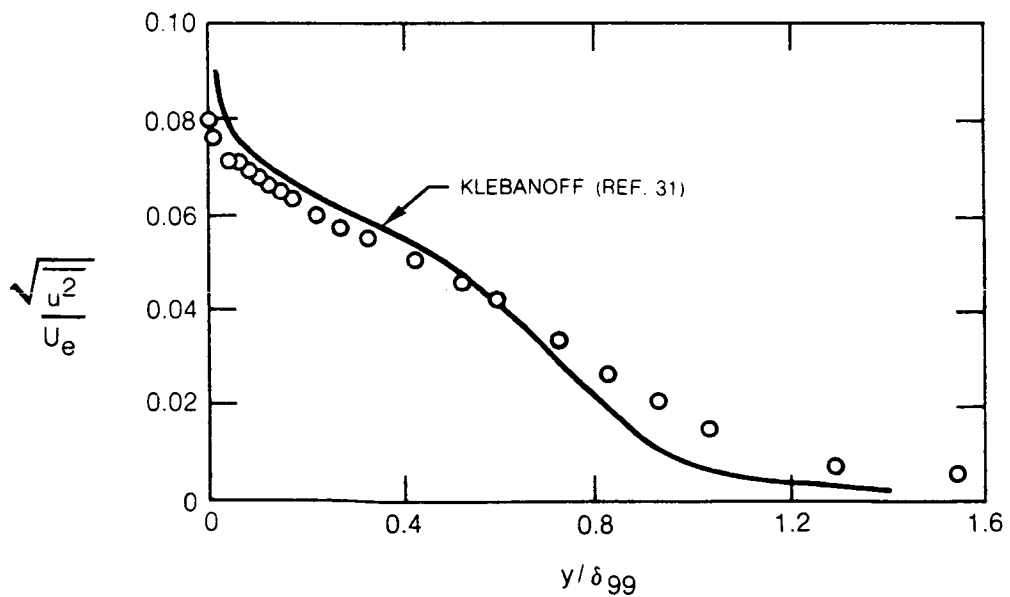


Figure 4-1 Spanwise and Transverse Total Pressure Distributions in Inlet Plane
 (Station 0, $x = -24.1 \text{ cm}$, -9.5 in.)

a) MEAN VELOCITY PROFILE PLOTTED IN "LAW-OF-THE-WALL" COORDINATES



b) STREAMWISE TURBULENCE INTENSITY NORMALIZED BY U_e COMPARED TO KLEBANOFF'S DATA



**Figure 4-2 Boundary Layer Characteristics at Initial Measurement Plane
(Station 0, $x = -24.1$ cm, -9.5 in.)**

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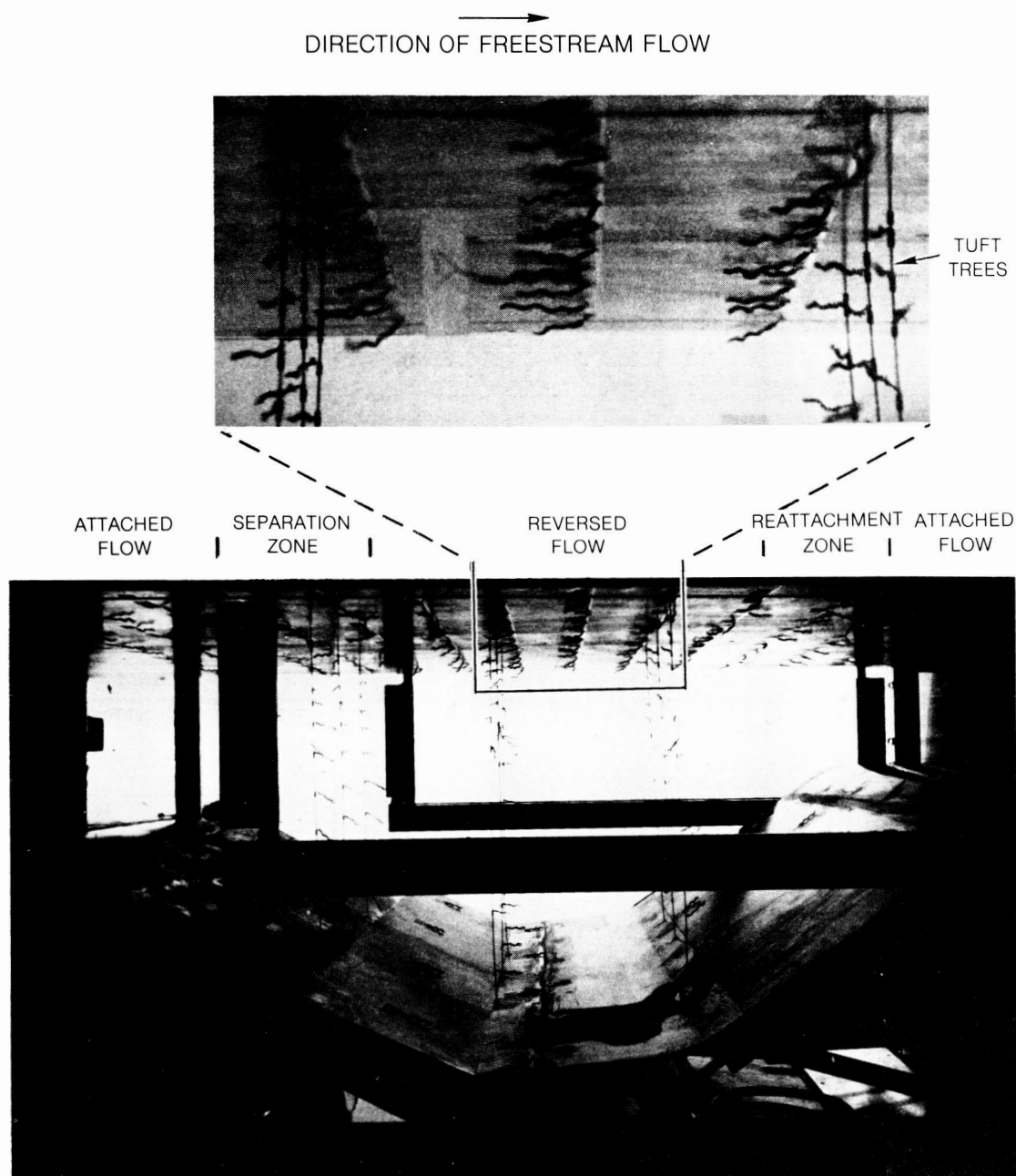


Figure 4-3 Tuft Flow Visualization

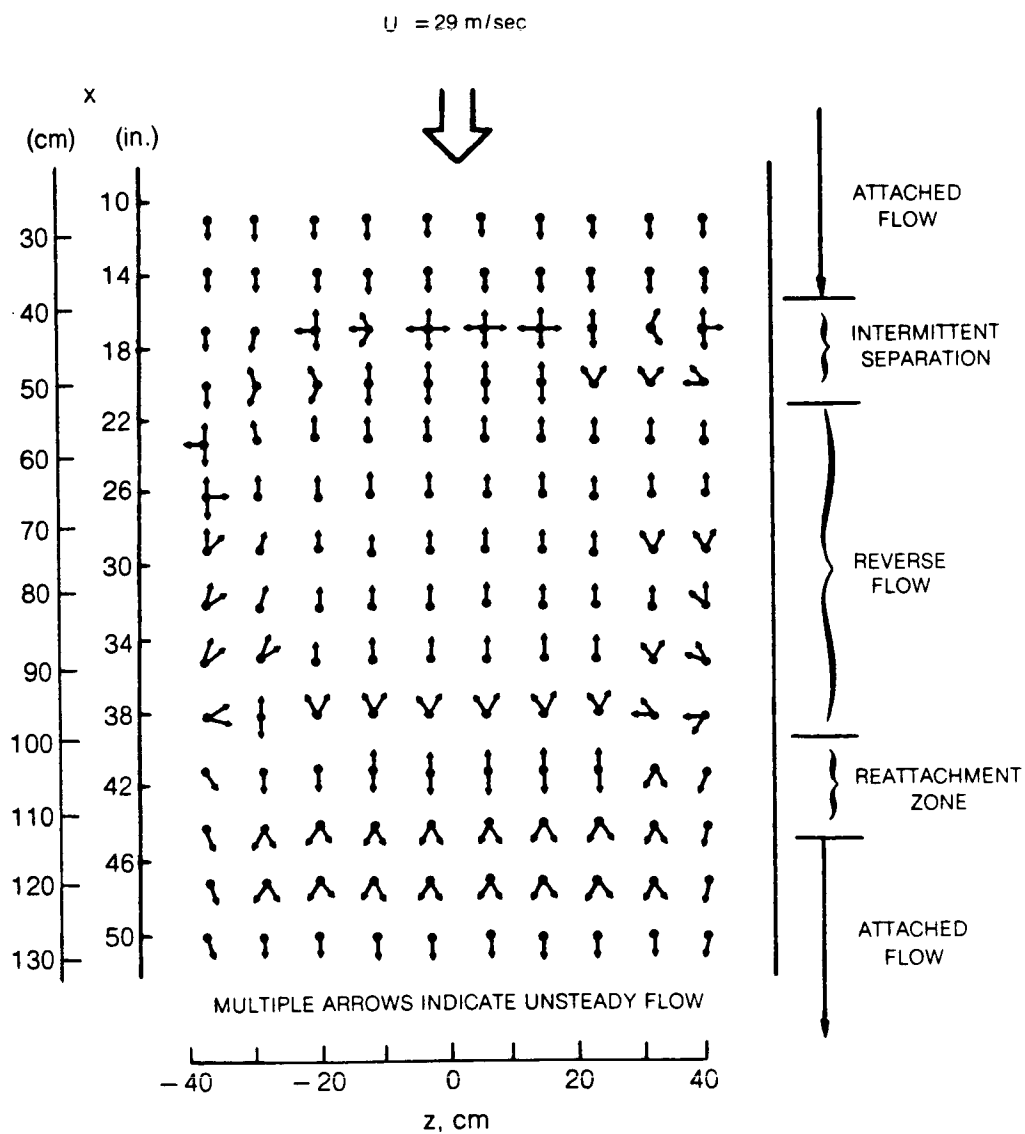
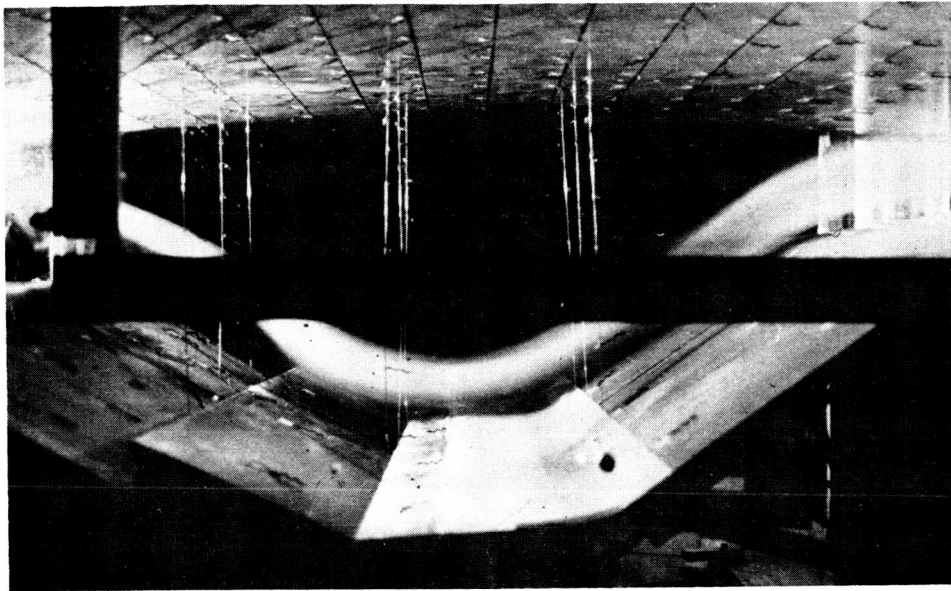


Figure 4-4 Surface Flow Directions on Test Plate as Indicated by Tufts

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SEPARATION REGION

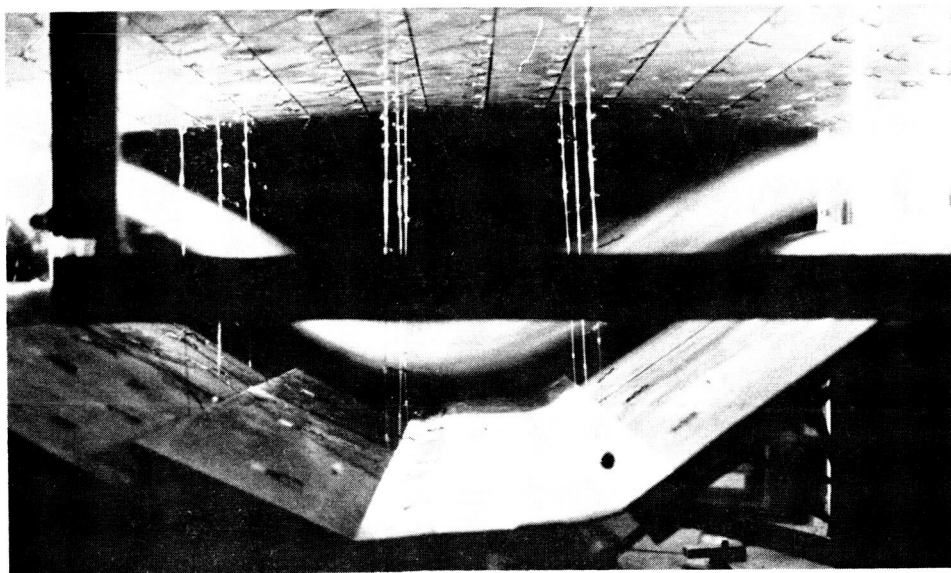
REATTACHMENT REGION



a) $y_{\text{probe}} = 10 \text{ cm}$

SEPARATION REGION

REATTACHMENT REGION



b) $y_{\text{probe}} = 7.6 \text{ cm}$

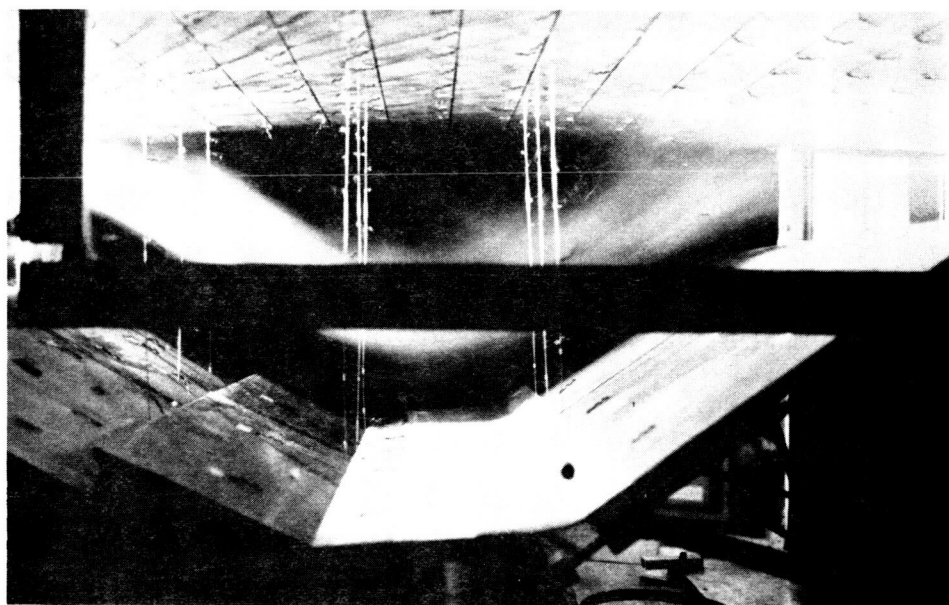
Figure 4-5 Smoke Flow Visualization of Separation Bubble

SEPARATION REGION



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REATTACHMENT REGION

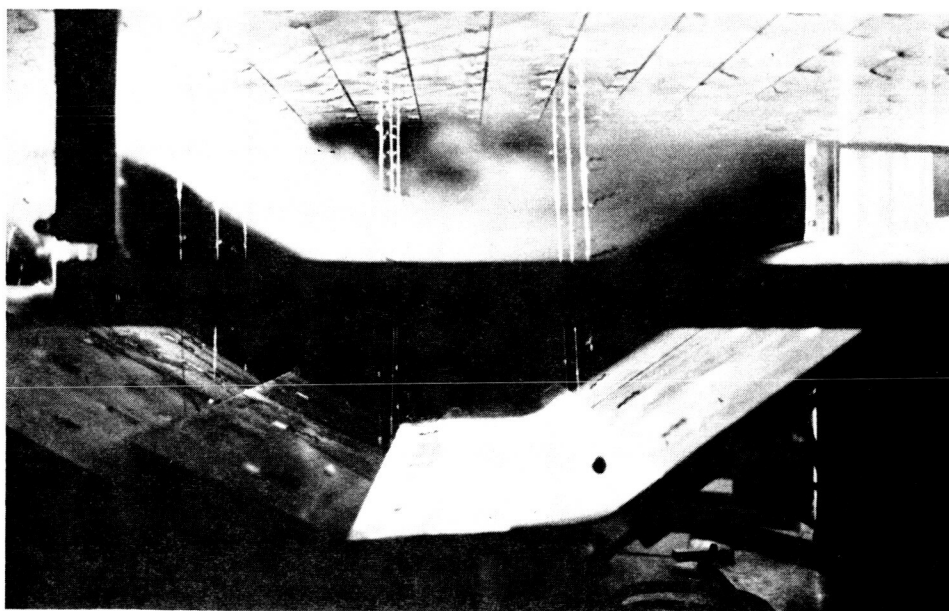


c) $y_{\text{probe}} = 6.4 \text{ cm}$

SEPARATION REGION



REATTACHMENT REGION



d) $y_{\text{probe}} = 5.1 \text{ cm}$

Figure 4-5 Smoke Flow Visualization of Separation Bubble (Concluded)

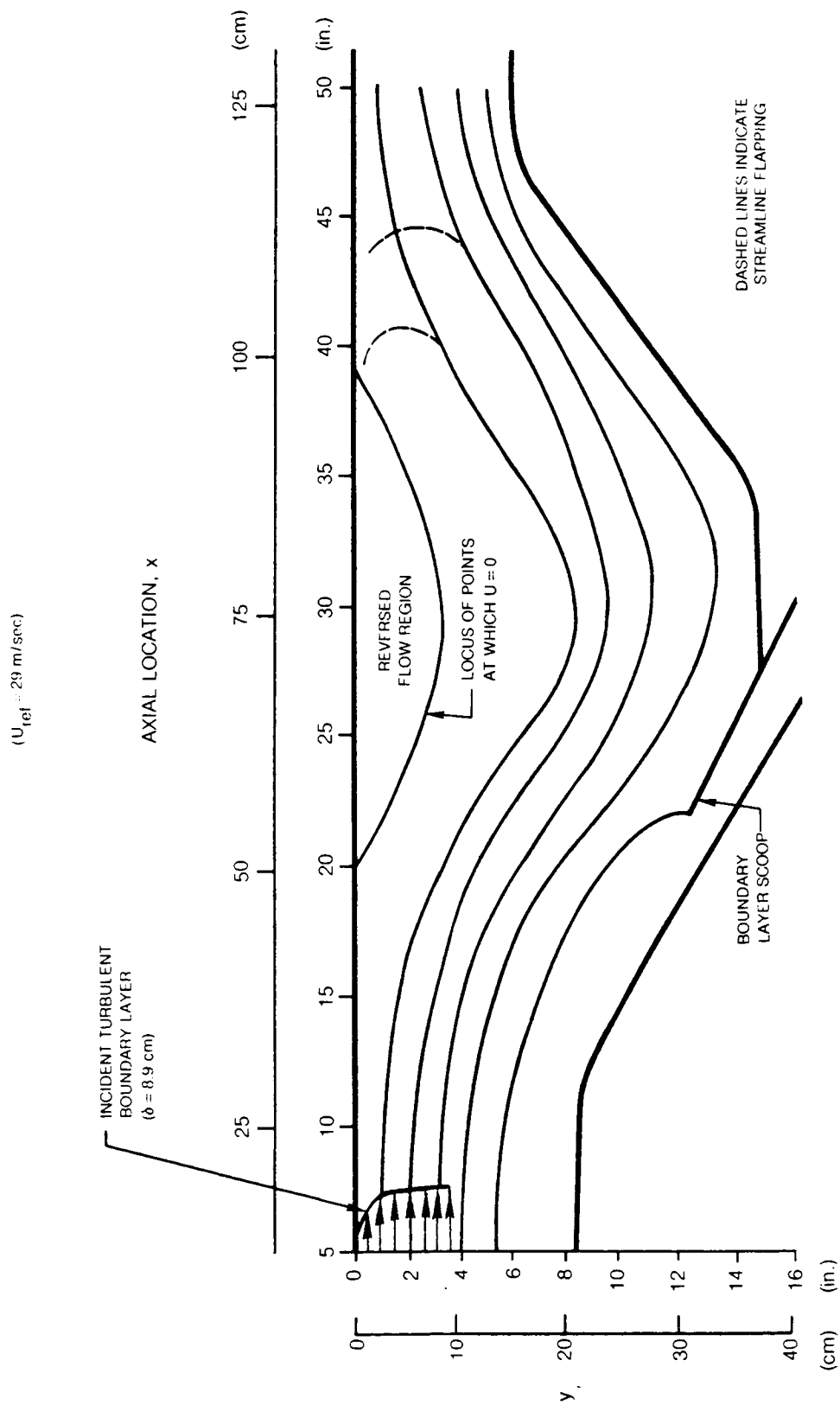


Figure 4-6 Streamlines Determined from Smoke Flow Visualization and Tuft Trees

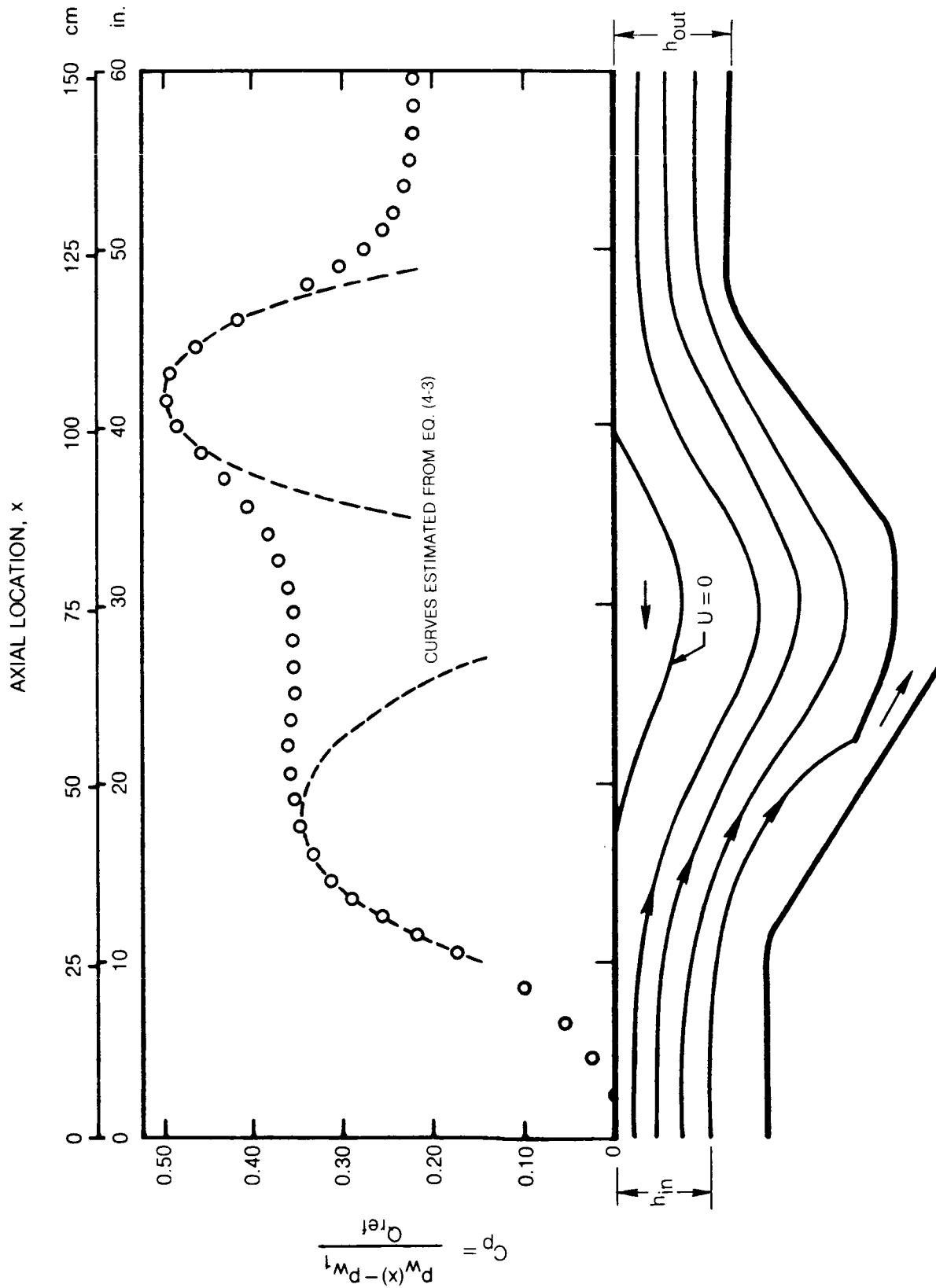


Figure 4-7 Test Surface Static Pressure Distribution on Tunnel Centerline

85-8-36-9

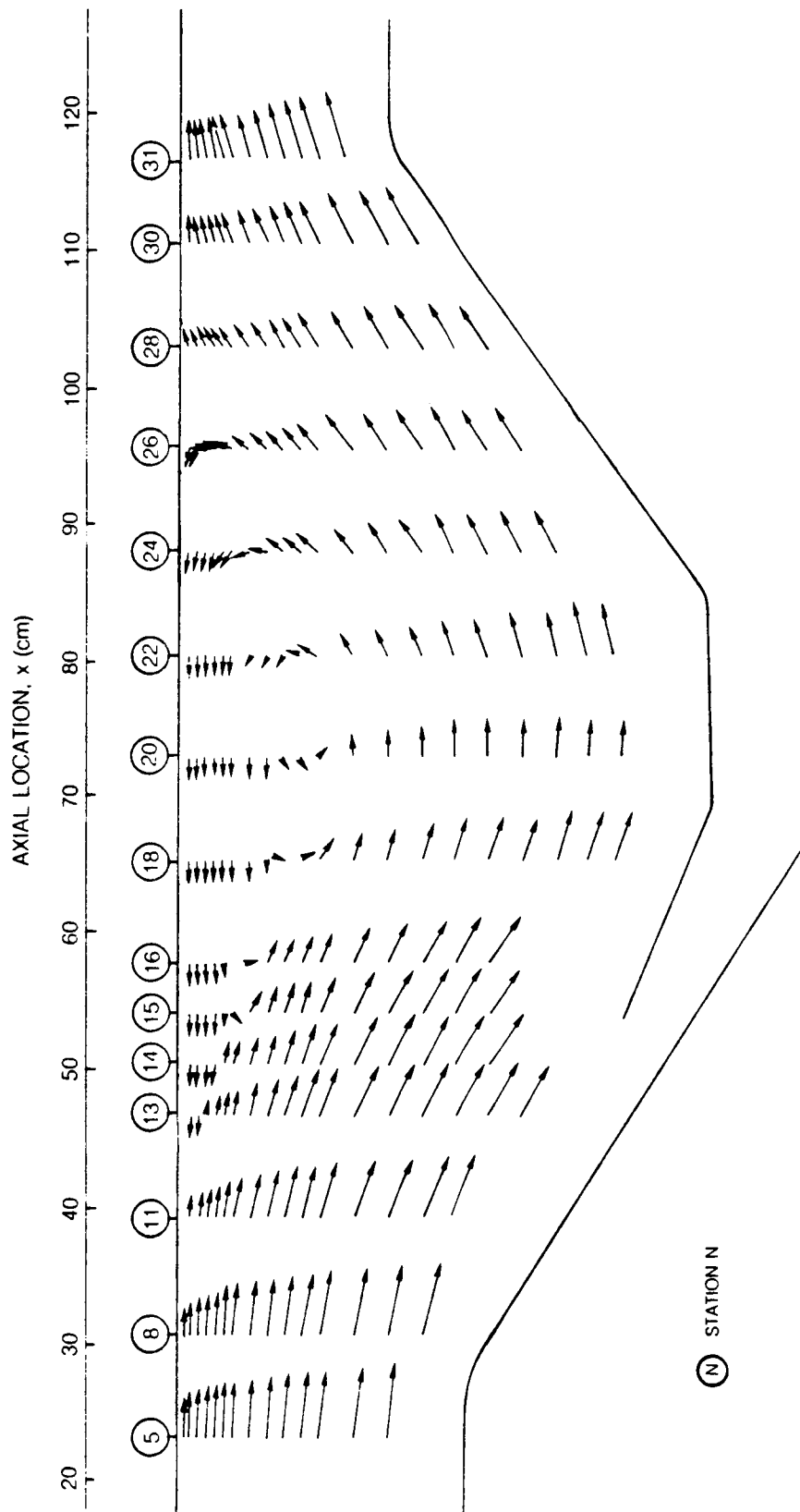


Figure 4-8 LV Mean Velocity Measurements on Wind Tunnel Centerline

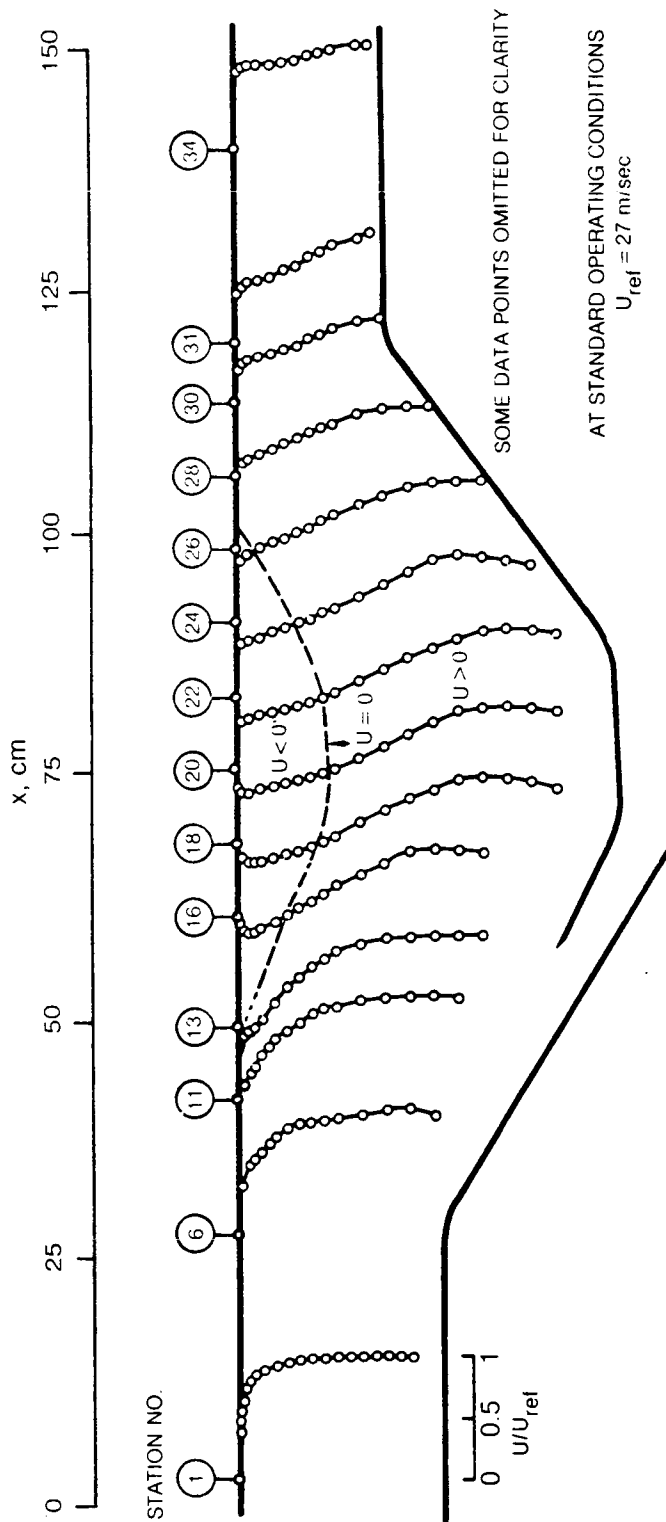


Figure 4-9 Nondimensional Axial Velocity Profiles, y vs $\frac{U}{U_{ref}}$

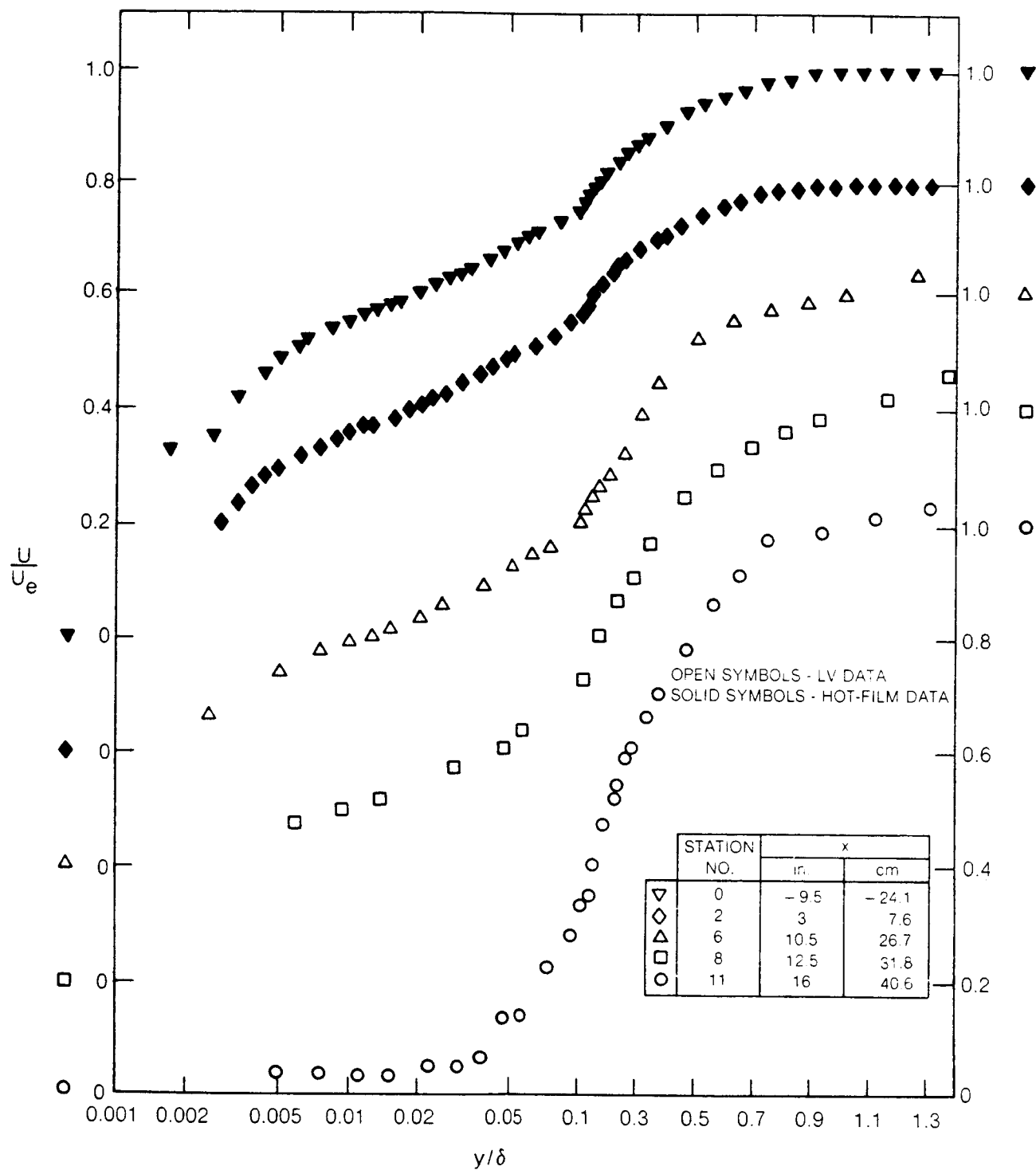


Figure 4-10a Non-Dimensional Axial Velocity Profiles. Note Log-Linear Abscissa and Displaced Ordinates

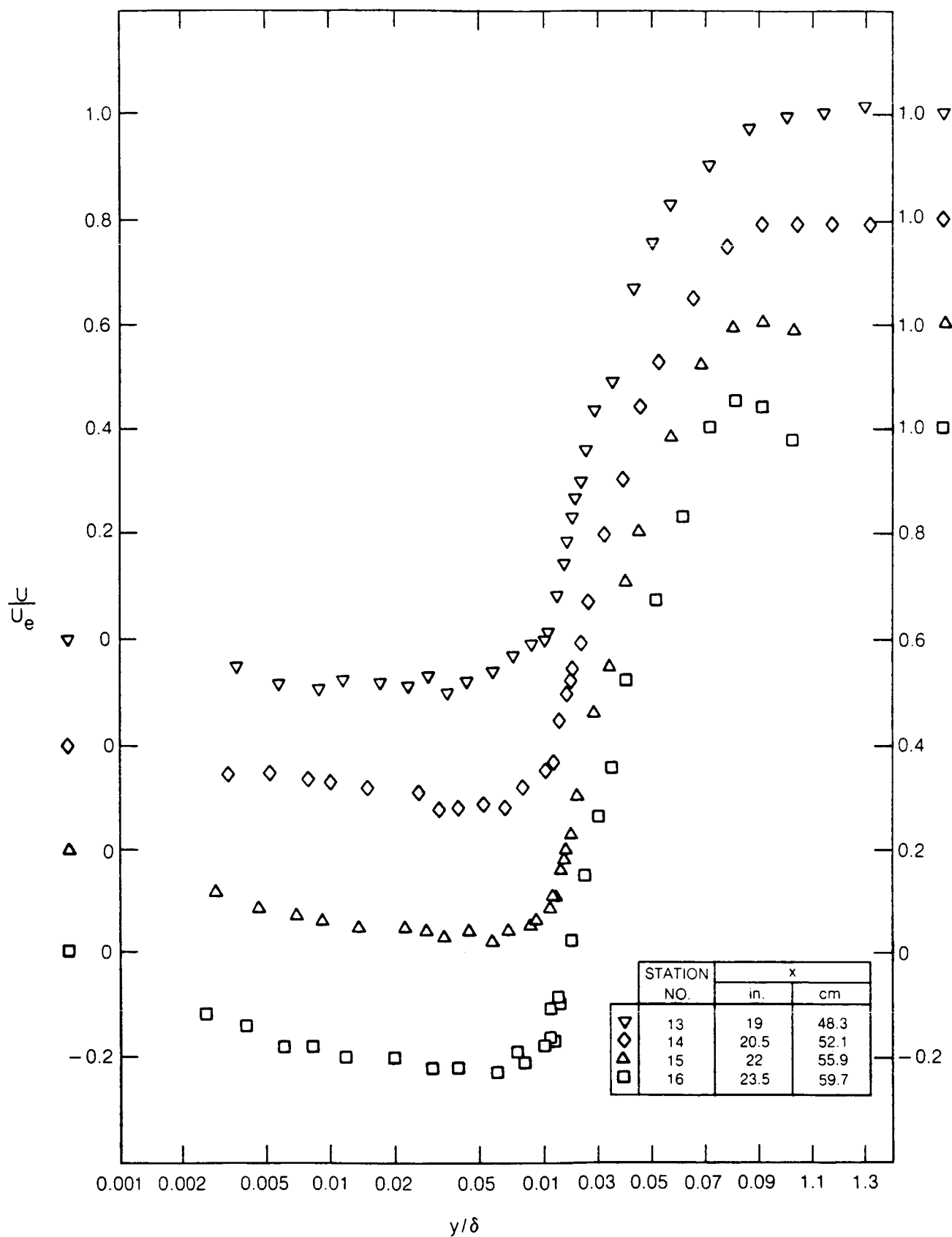


Figure 4-10b Non-Dimensional Axial Velocity Profiles. Note Log-Linear Abscissa and Displaced Ordinates (Continued)

84-8-1-20

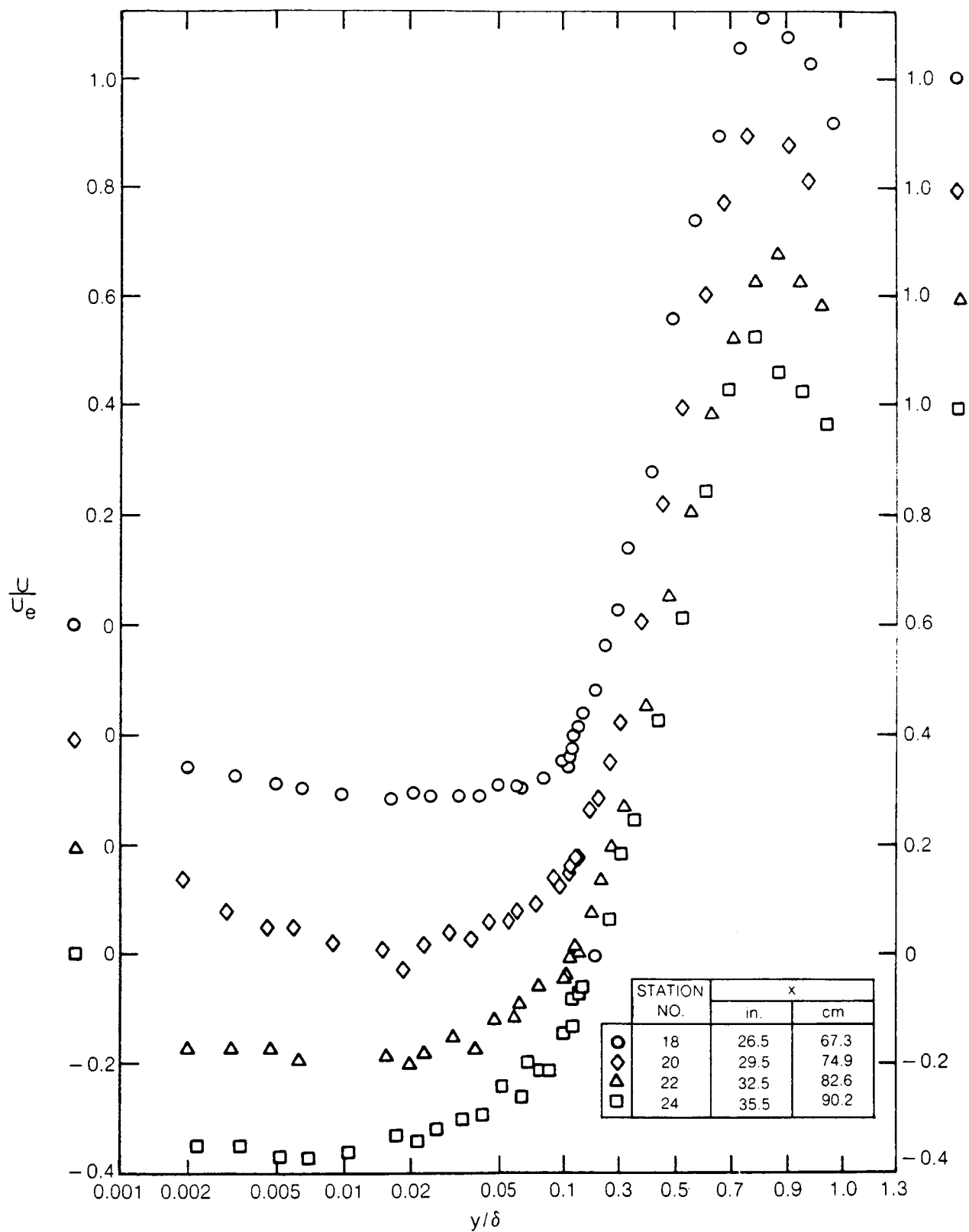


Figure 4-10c Non-Dimensional Axial Velocity Profiles. Note Log-Linear Abscissa and Displaced Ordinates (Continued)

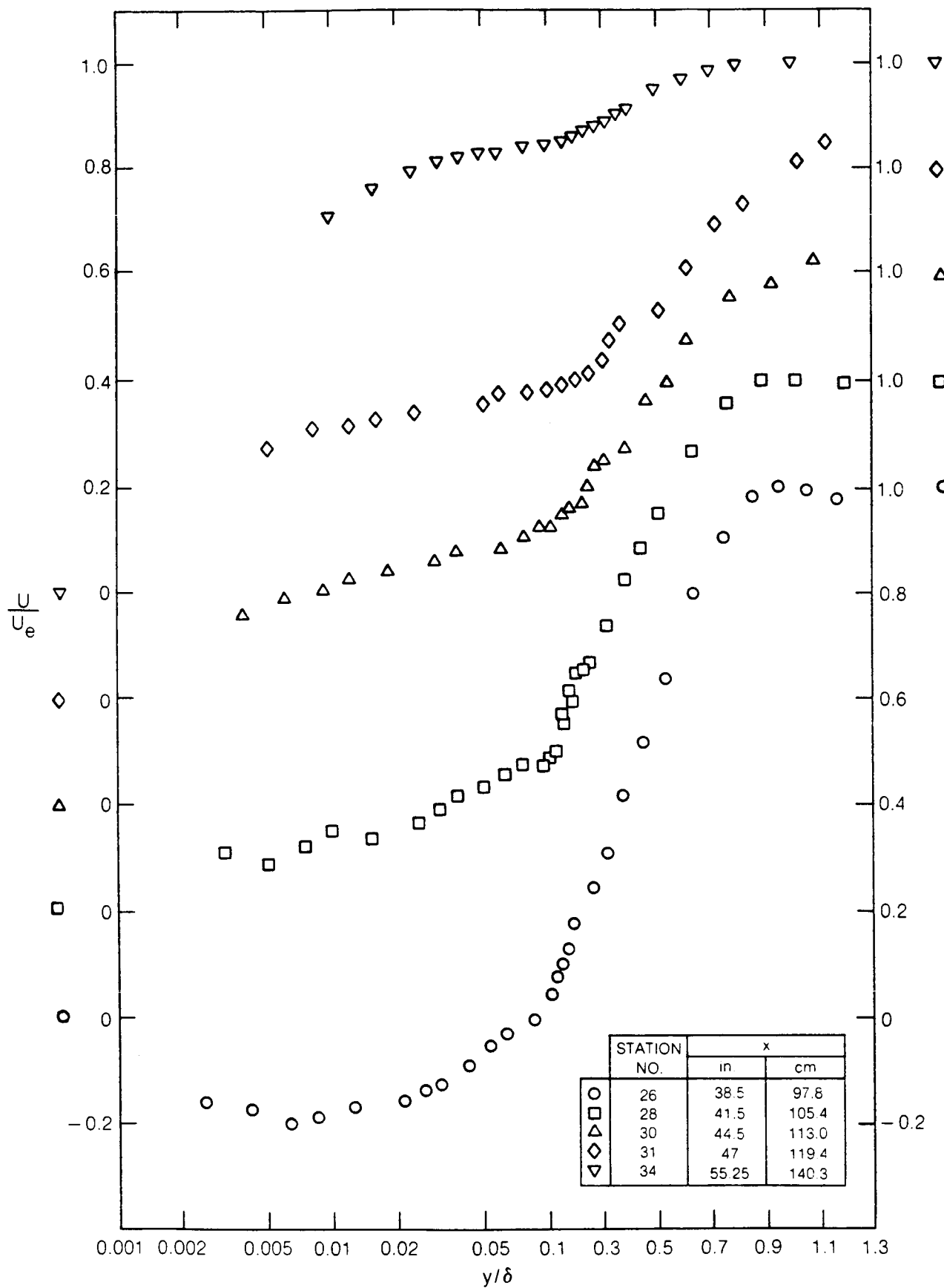


Figure 4-10d Non-Dimensional Axial Velocity Profiles. Note Log-Linear Abscissa and Displaced Ordinates (Concluded)

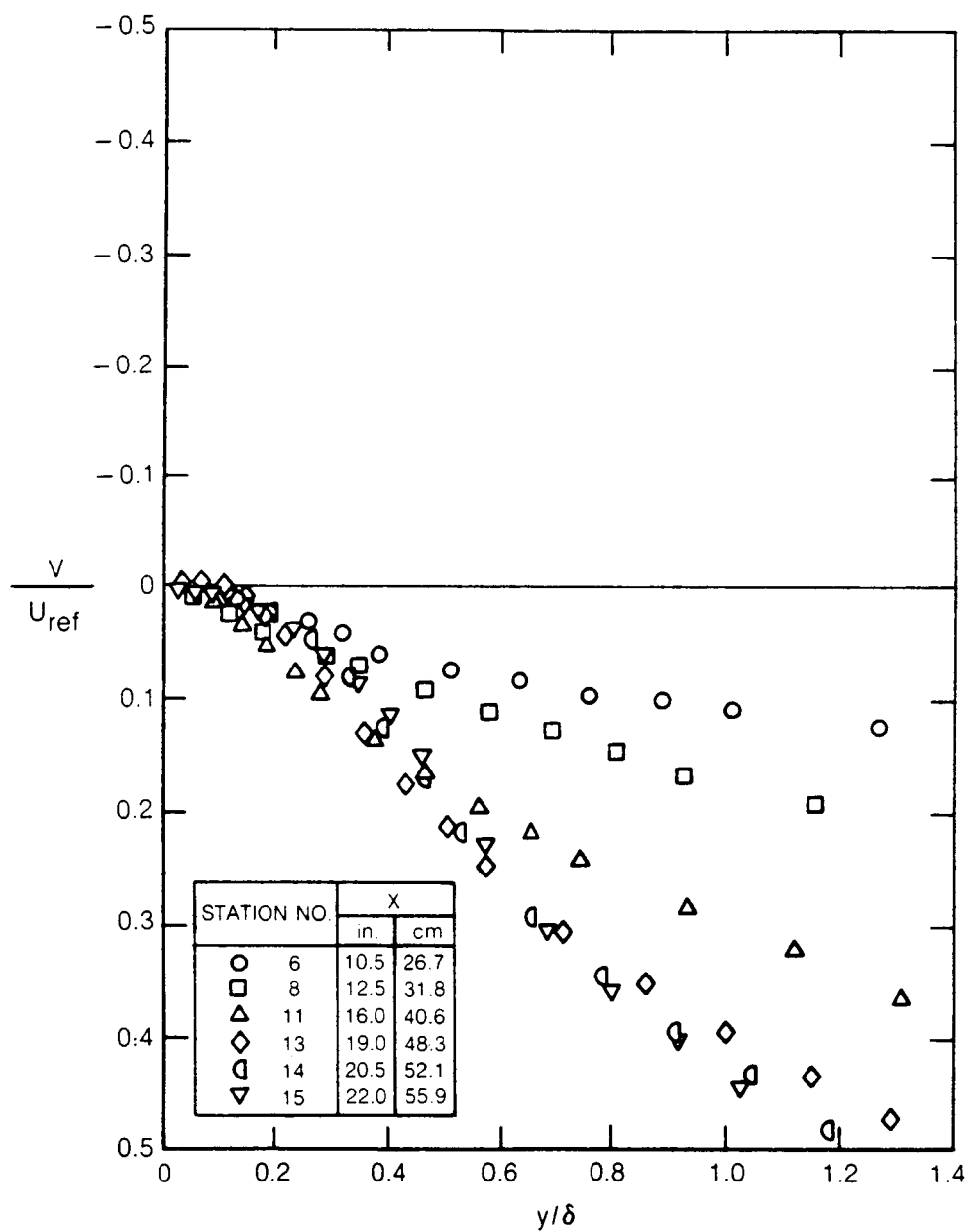


Figure 4-11a LV Measurements of Transverse Velocity Profiles

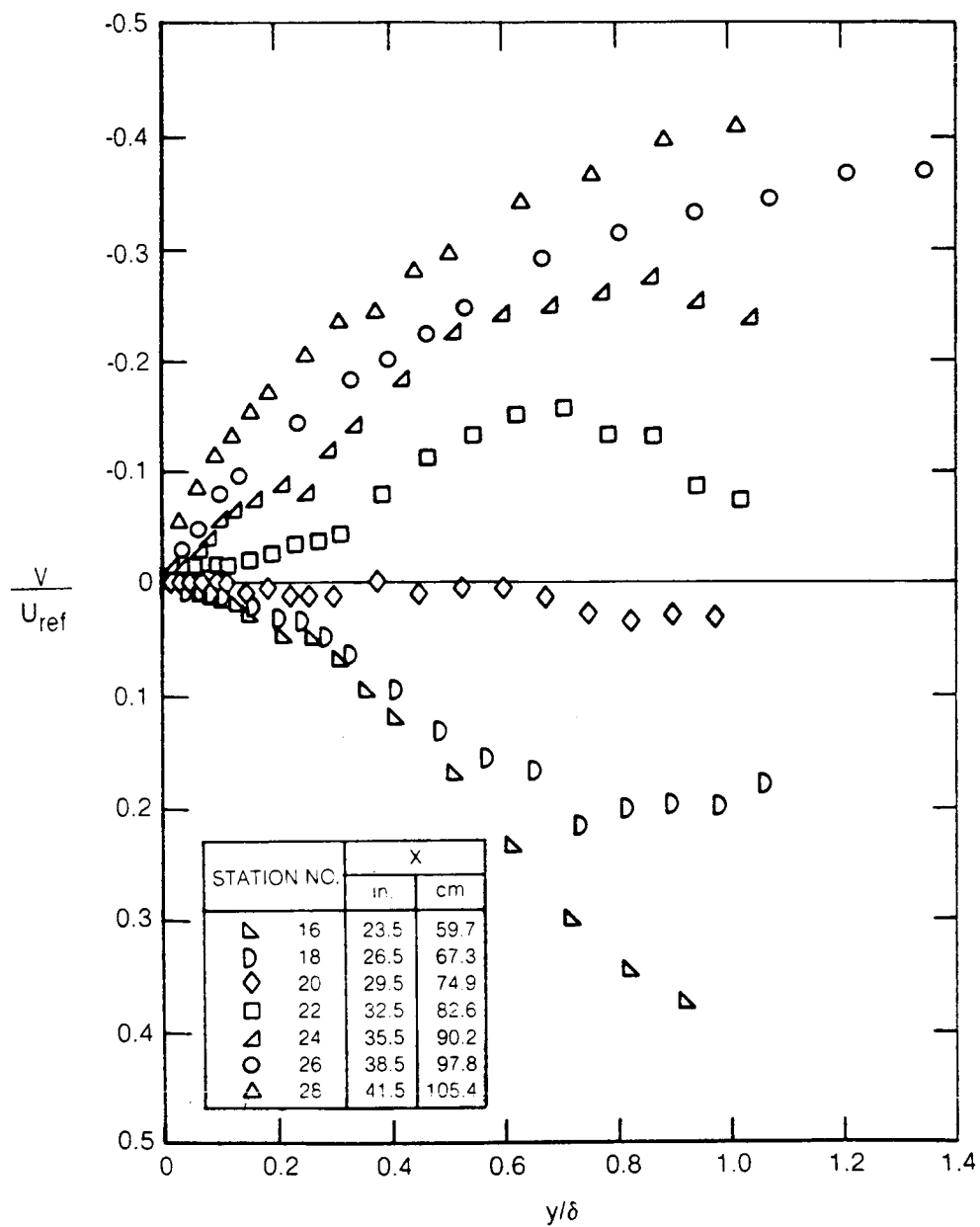


Figure 4-11b LV Measurements of Transverse Velocity Profiles (Continued)

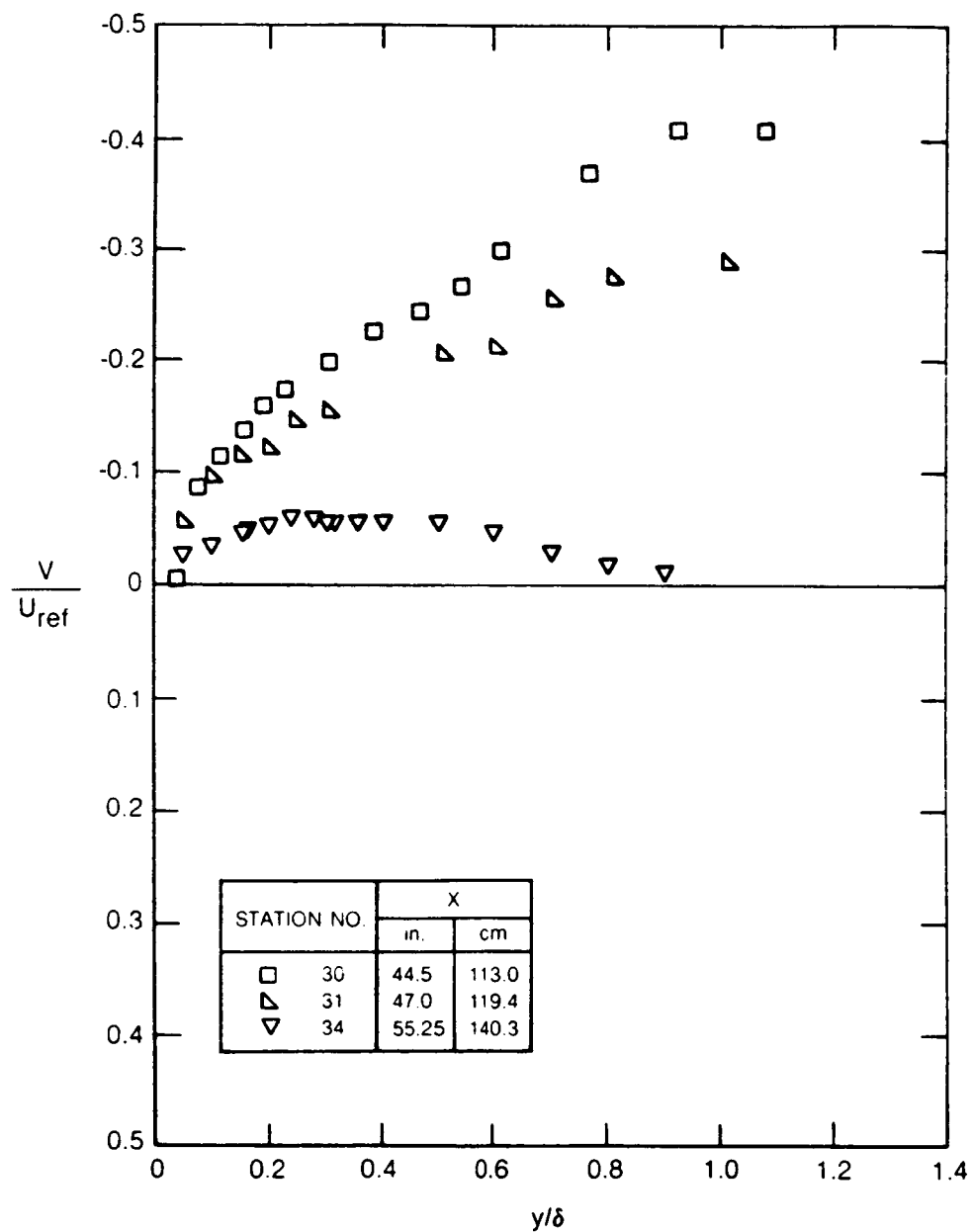


Figure 4-11c LV Measurements of Transverse Velocity Profiles (Concluded)

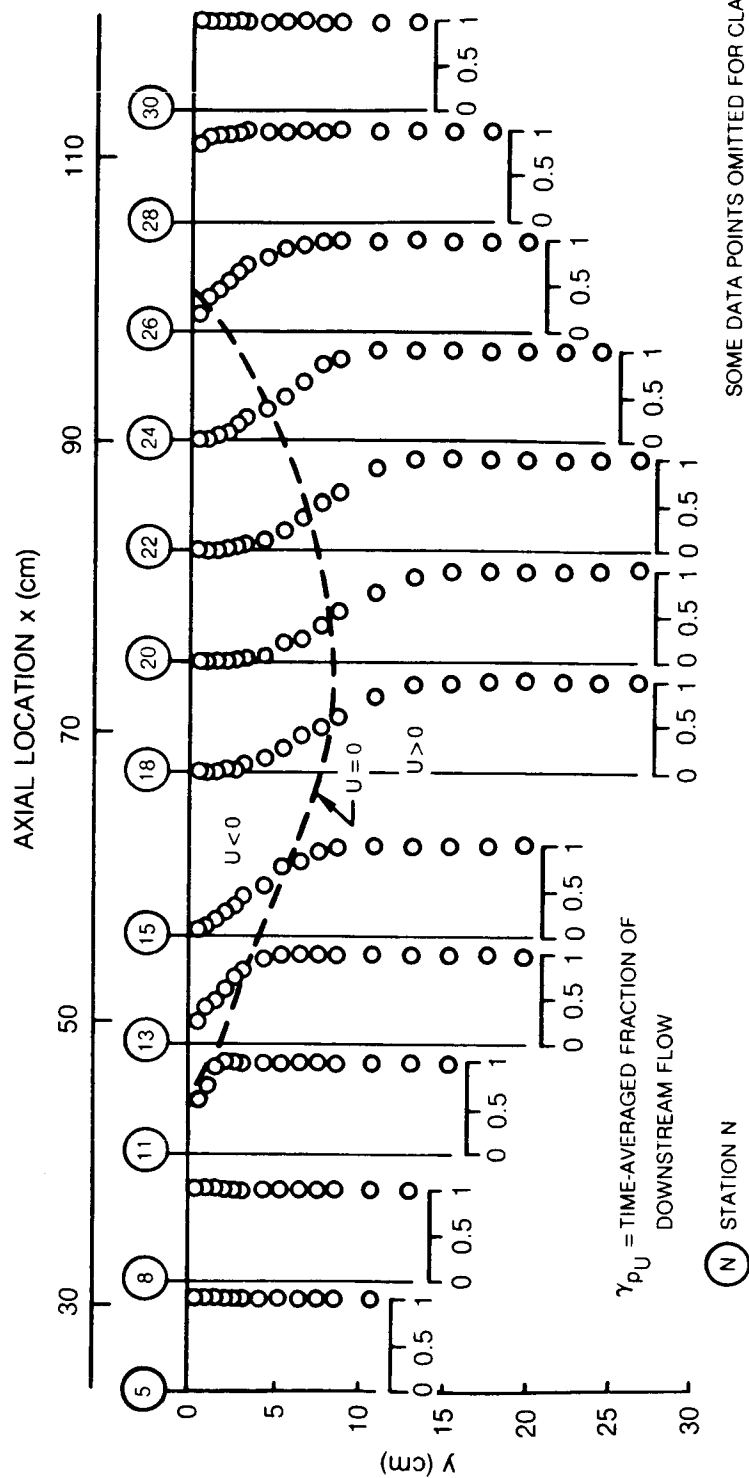


Figure 4-12 Forward Flow Fraction (γ_{PU}) Profiles Determined from LV Histograms ($z = 0$)

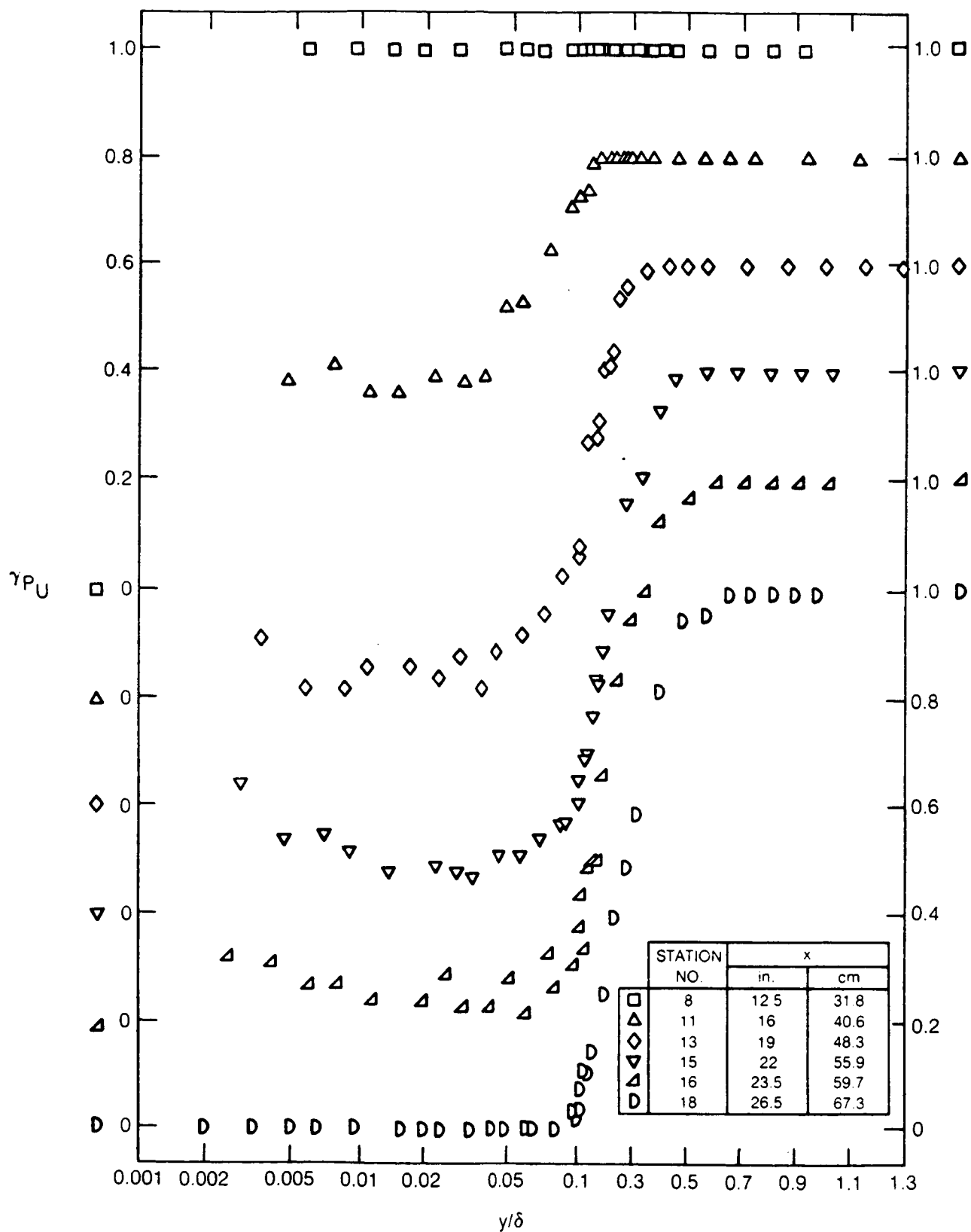


Figure 4-13a Forward Flow Fraction Profiles - Note Log-Linear Abscissa and Displaced Ordinates

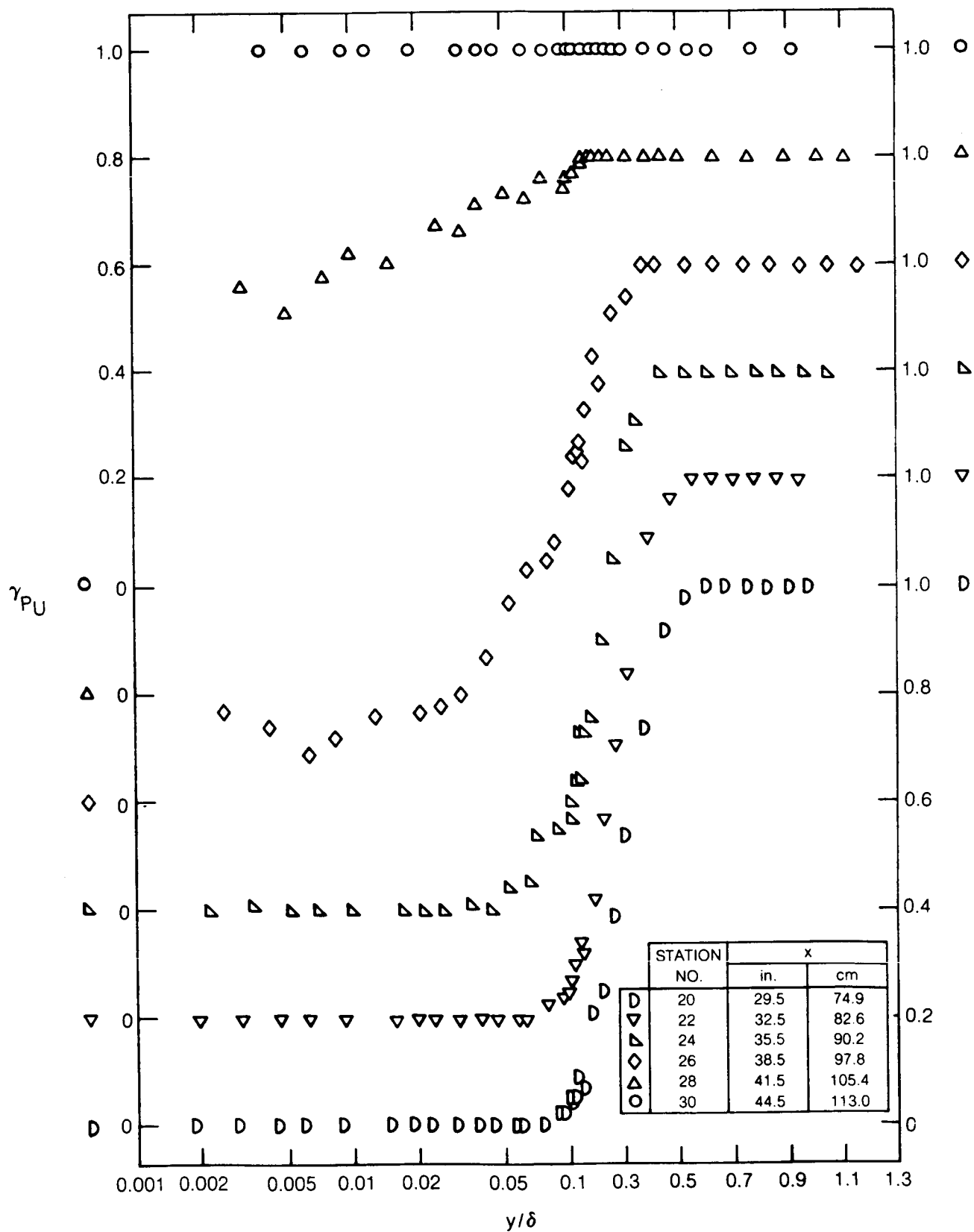
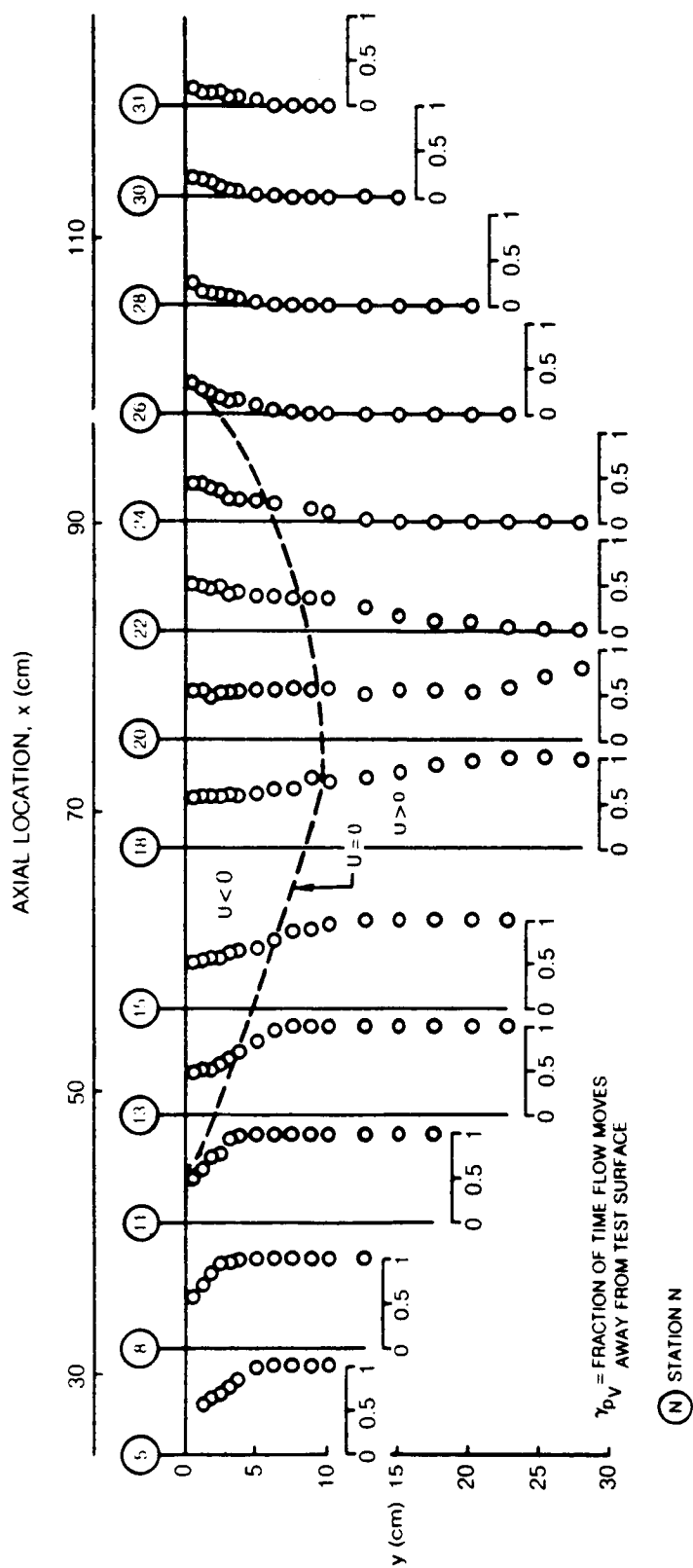


Figure 4-13b Forward Flow Fraction Profiles – Note Log-Linear Abscissa and Displaced Ordinates (Concluded)



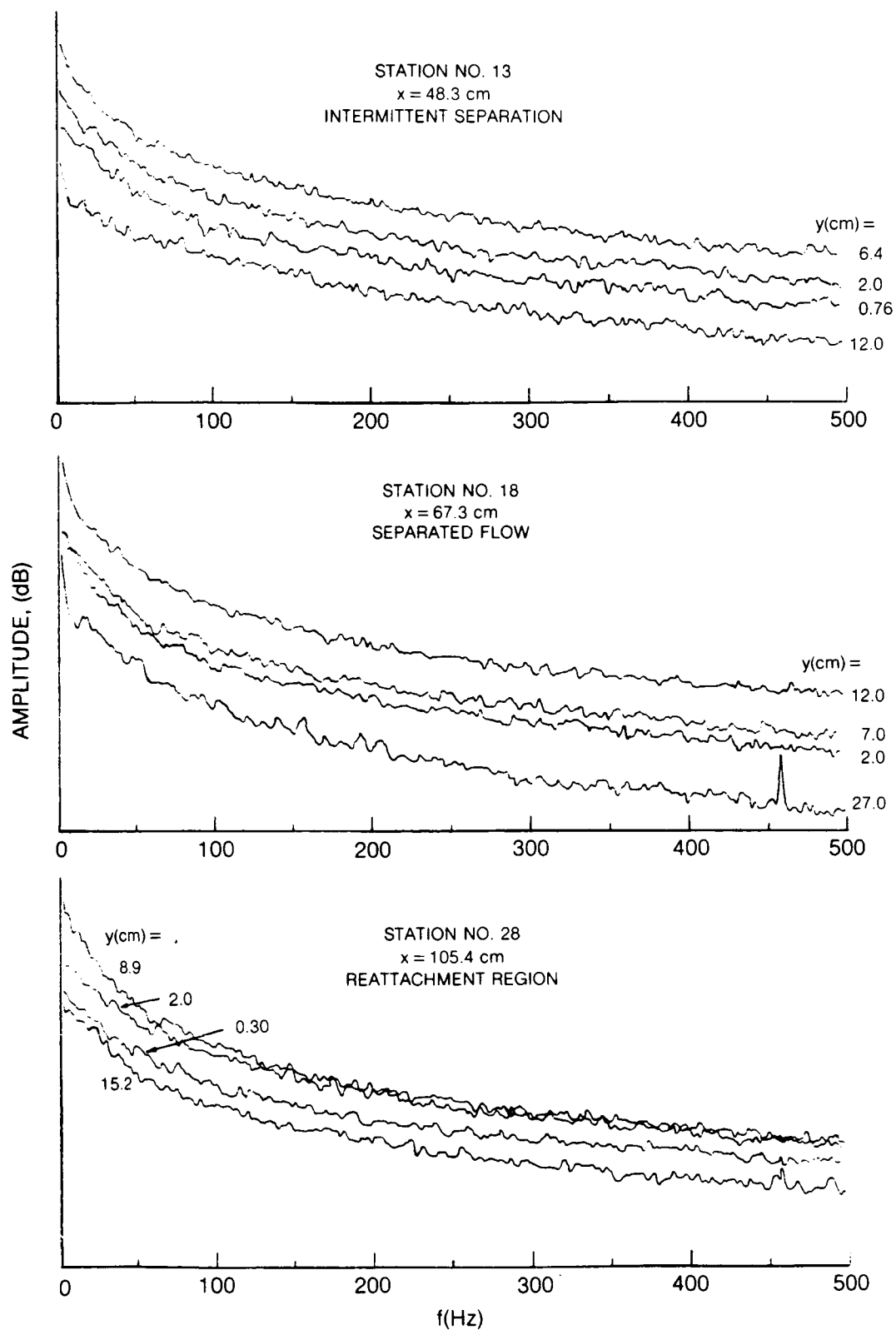


Figure 4-15 Spectra of Streamwise Turbulence Component Measured with Hot-Film

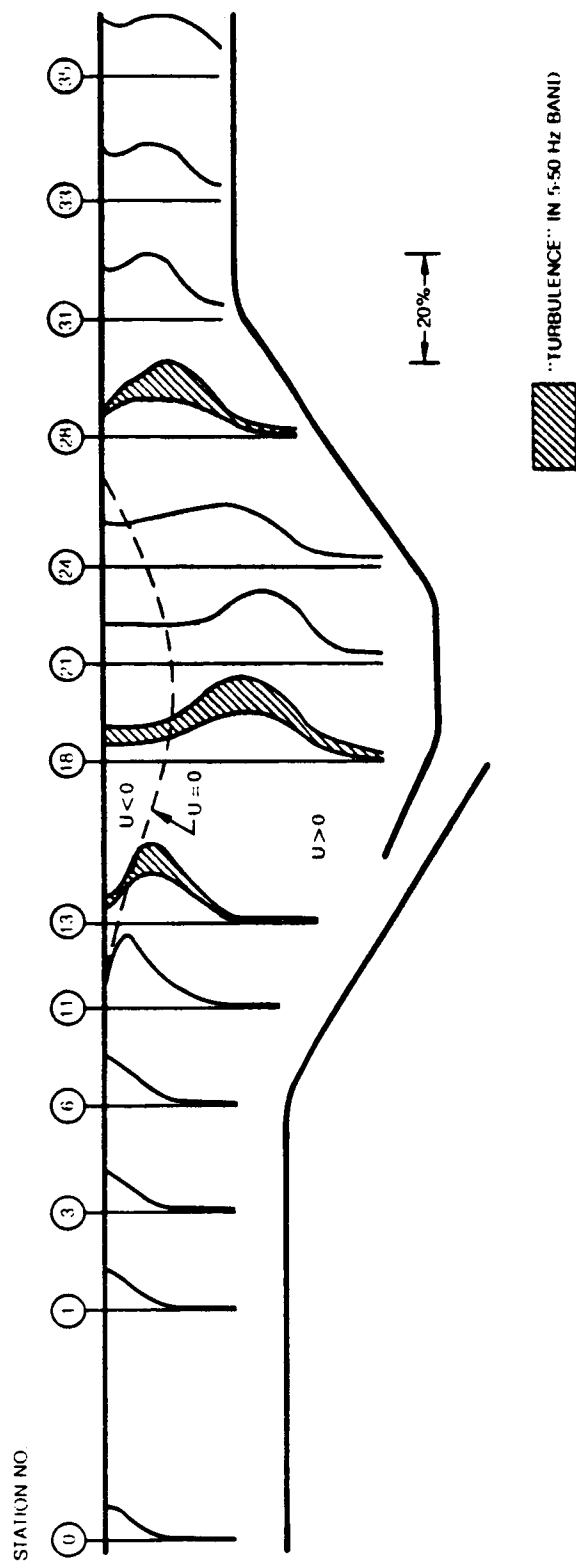
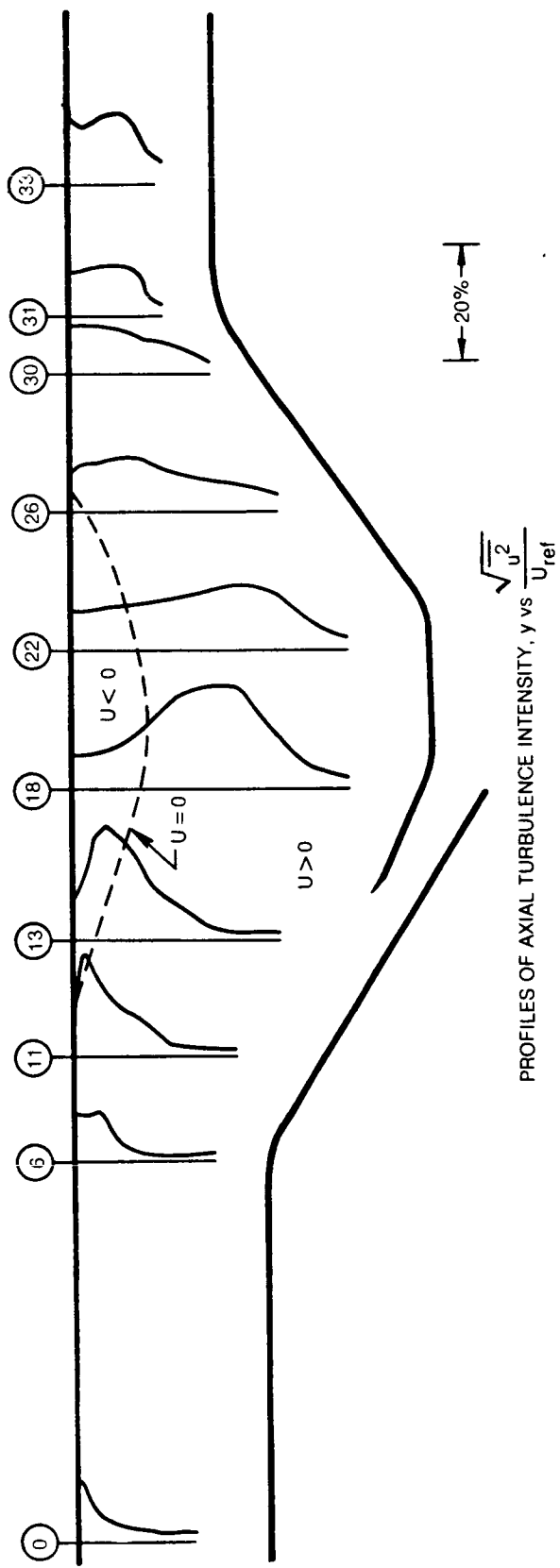


Figure 4-16 Profiles of Streamwise Turbulence Levels, y vs $\frac{\sqrt{q^2}}{U_{ref}}$, Measured with Hot-Film Showing Flow Unsteadiness

STATION NO.



STATION NO.

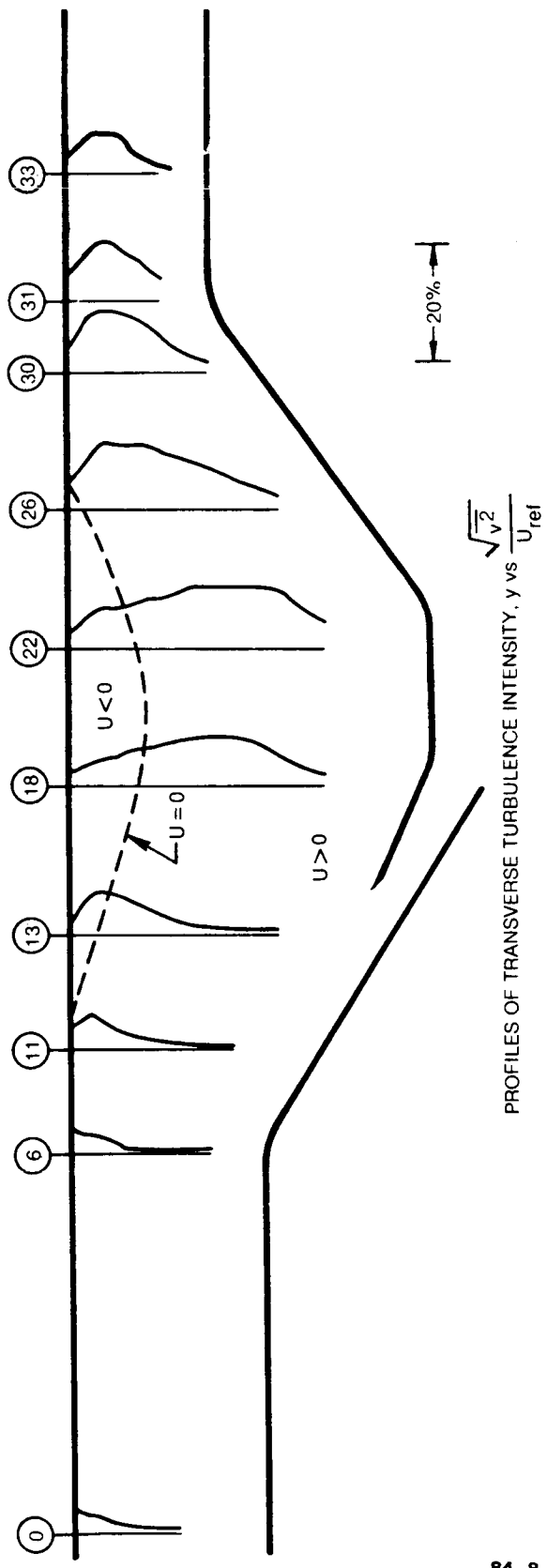


Figure 4-17 Turbulence Profiles Measured by Laser Velocimeter

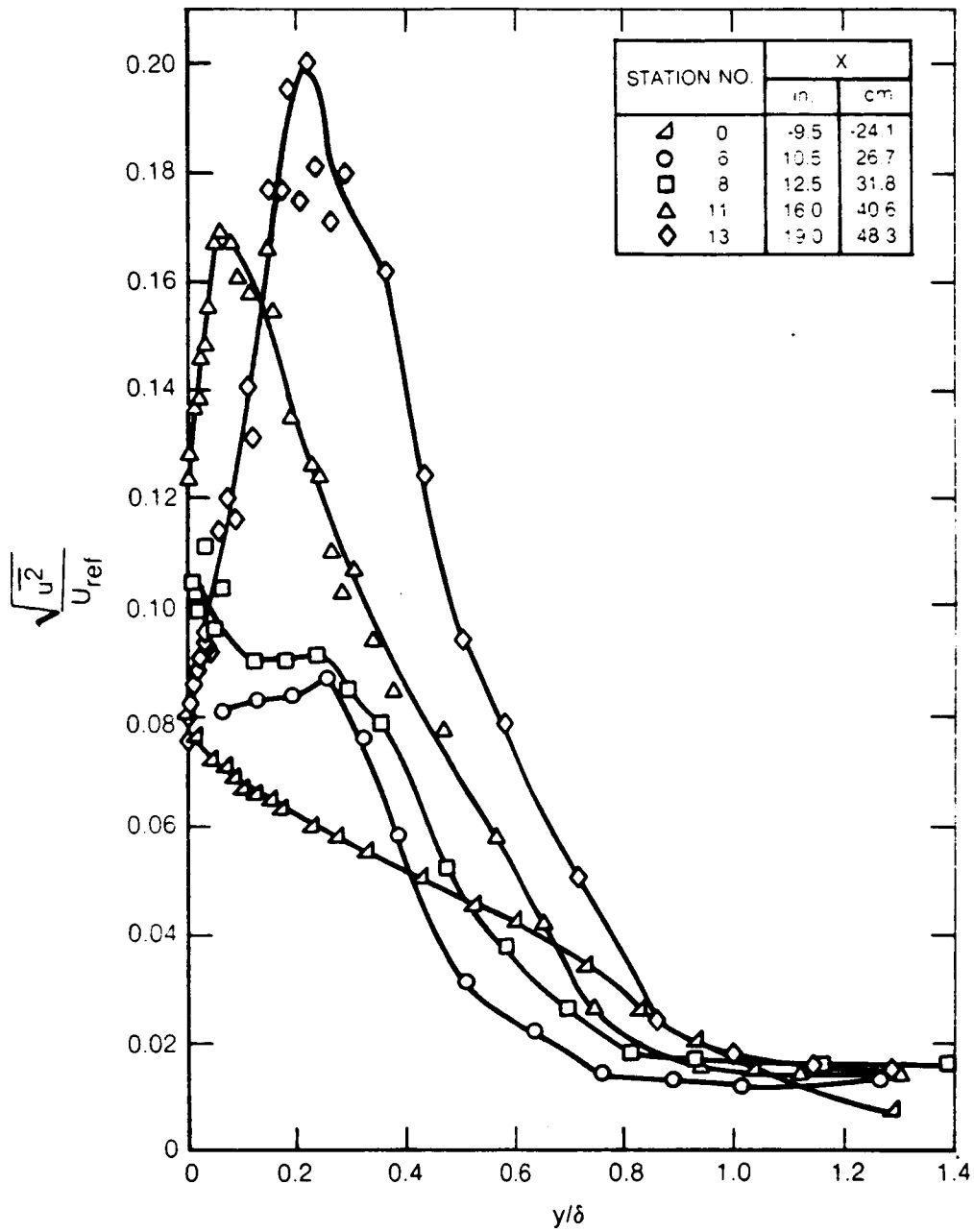


Figure 4-18a Nondimensional Axial Turbulence Profiles ($z = 0$)

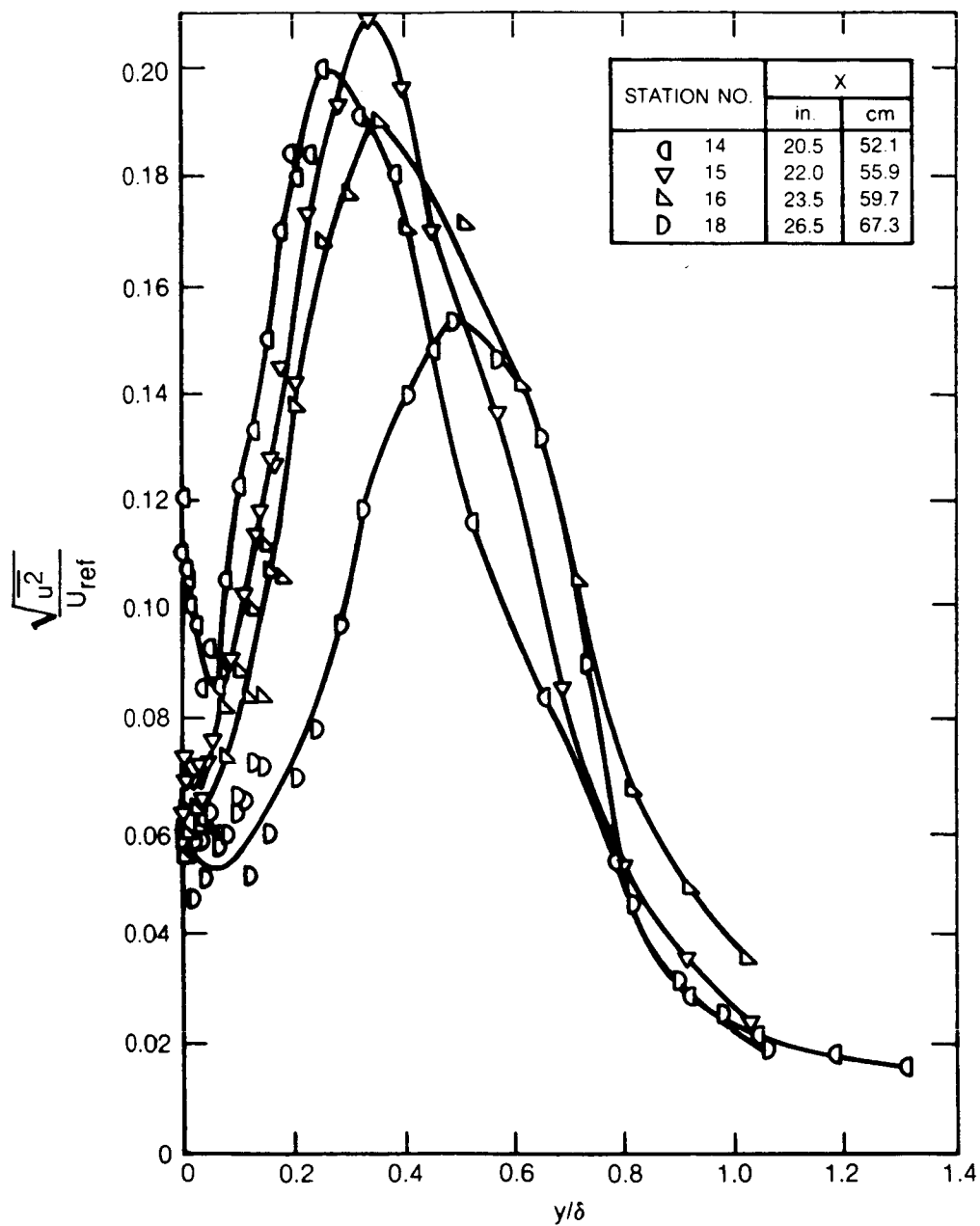


Figure 4-18b Nondimensional Axial Turbulence Profiles ($z = 0$) (Continued)

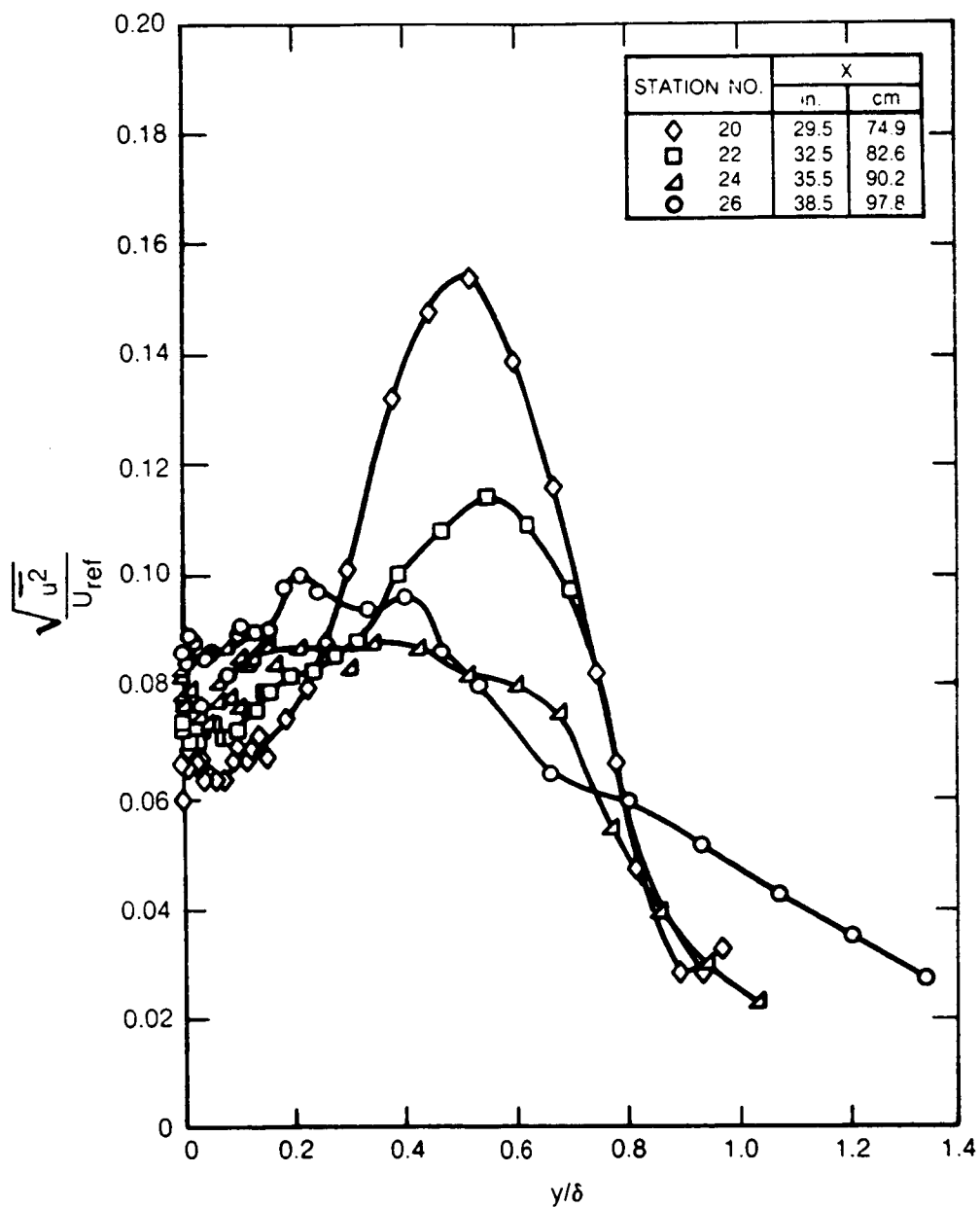


Figure 4-18c Nondimensional Axial Turbulence Profiles ($z = 0$) (Continued)

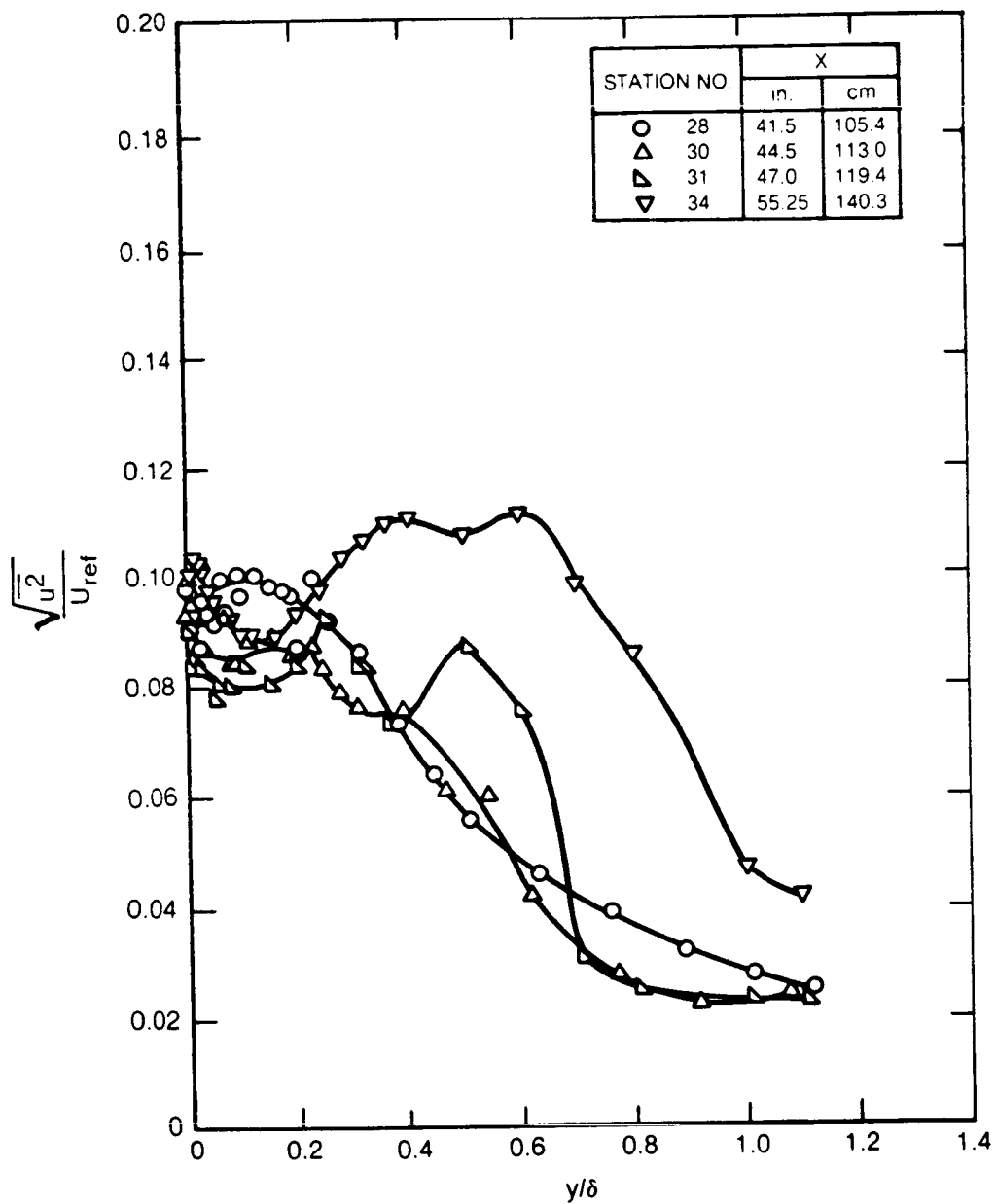


Figure 4-18d Nondimensional Axial Turbulence Profiles ($z = 0$) (Concluded)

84-8-1-42

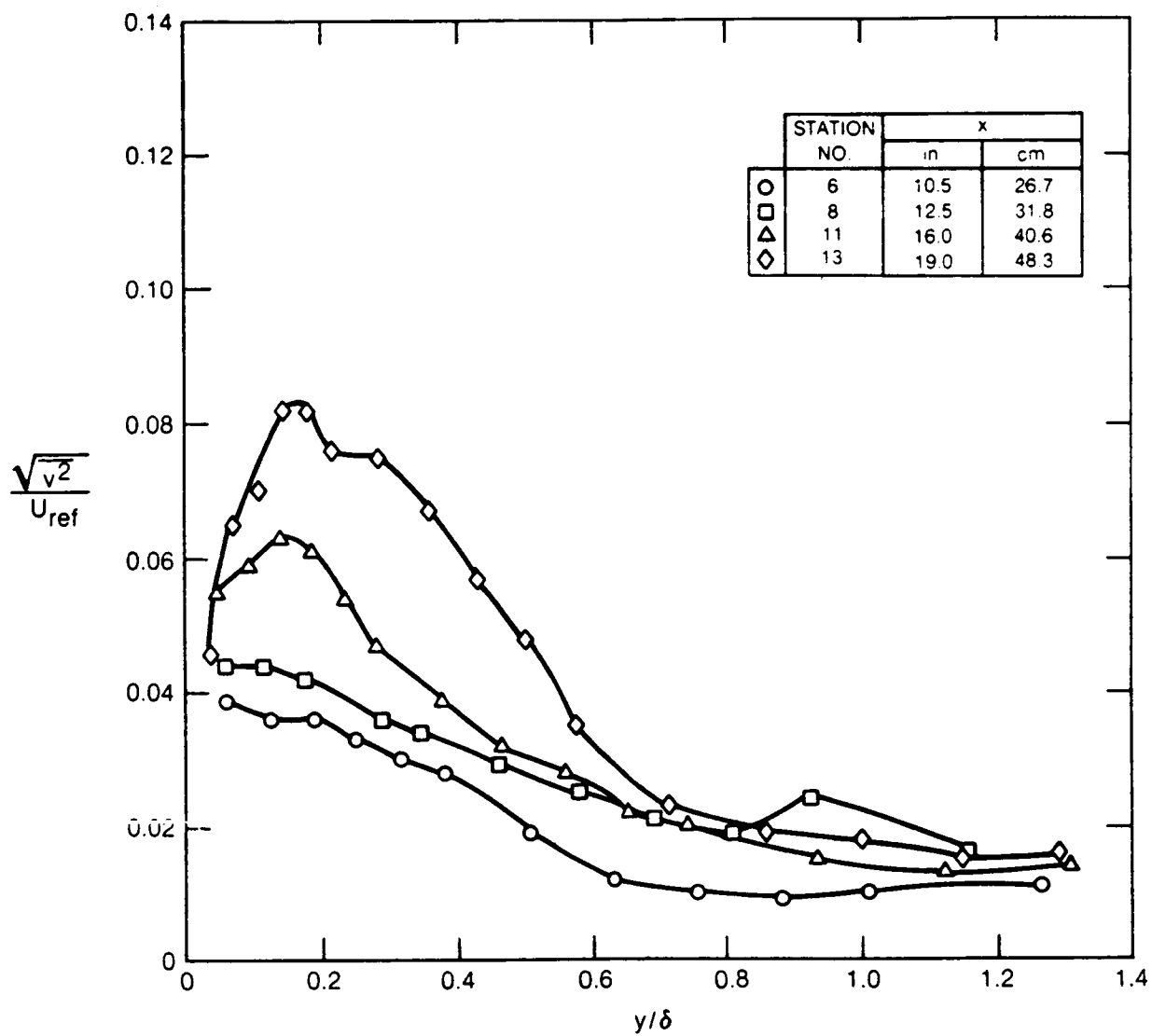


Figure 4-19a Non - Dimensional Transverse Turbulence Profiles

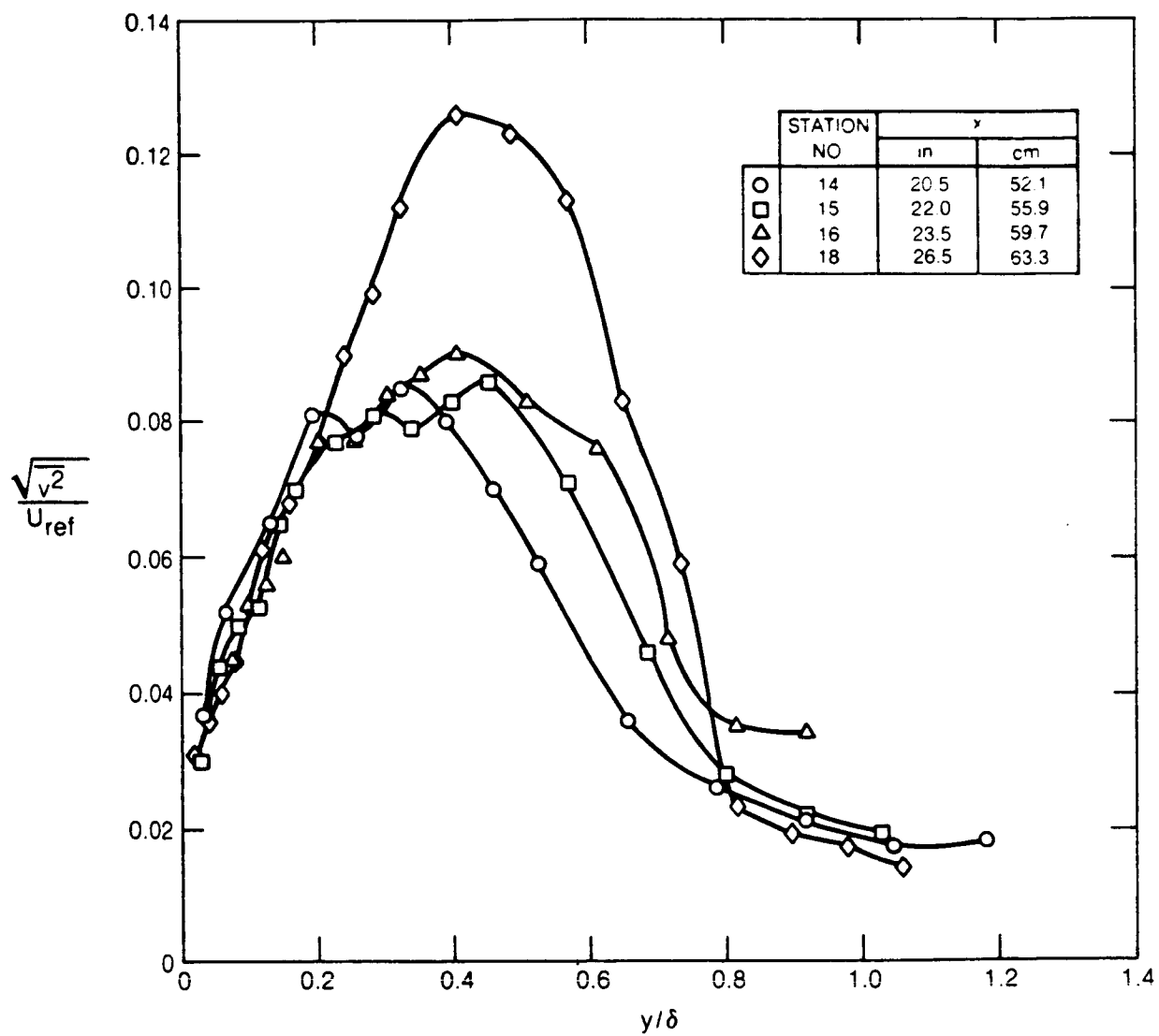


Figure 4-19b Non - Dimensional Transverse Turbulence Profiles (Continued)

84-8-1-68

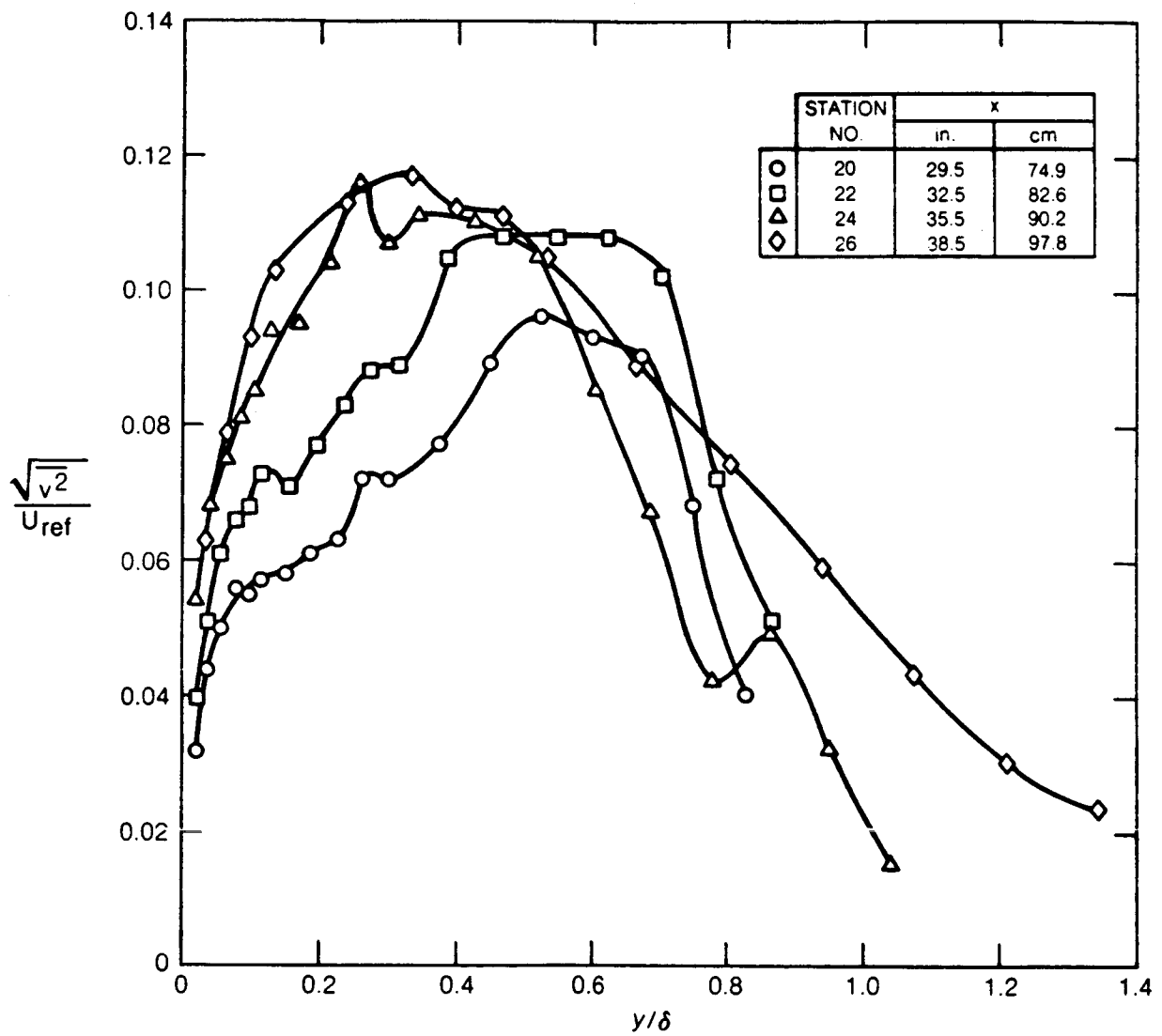


Figure 4-19c Non - Dimensional Transverse Turbulence Profile (Continued)

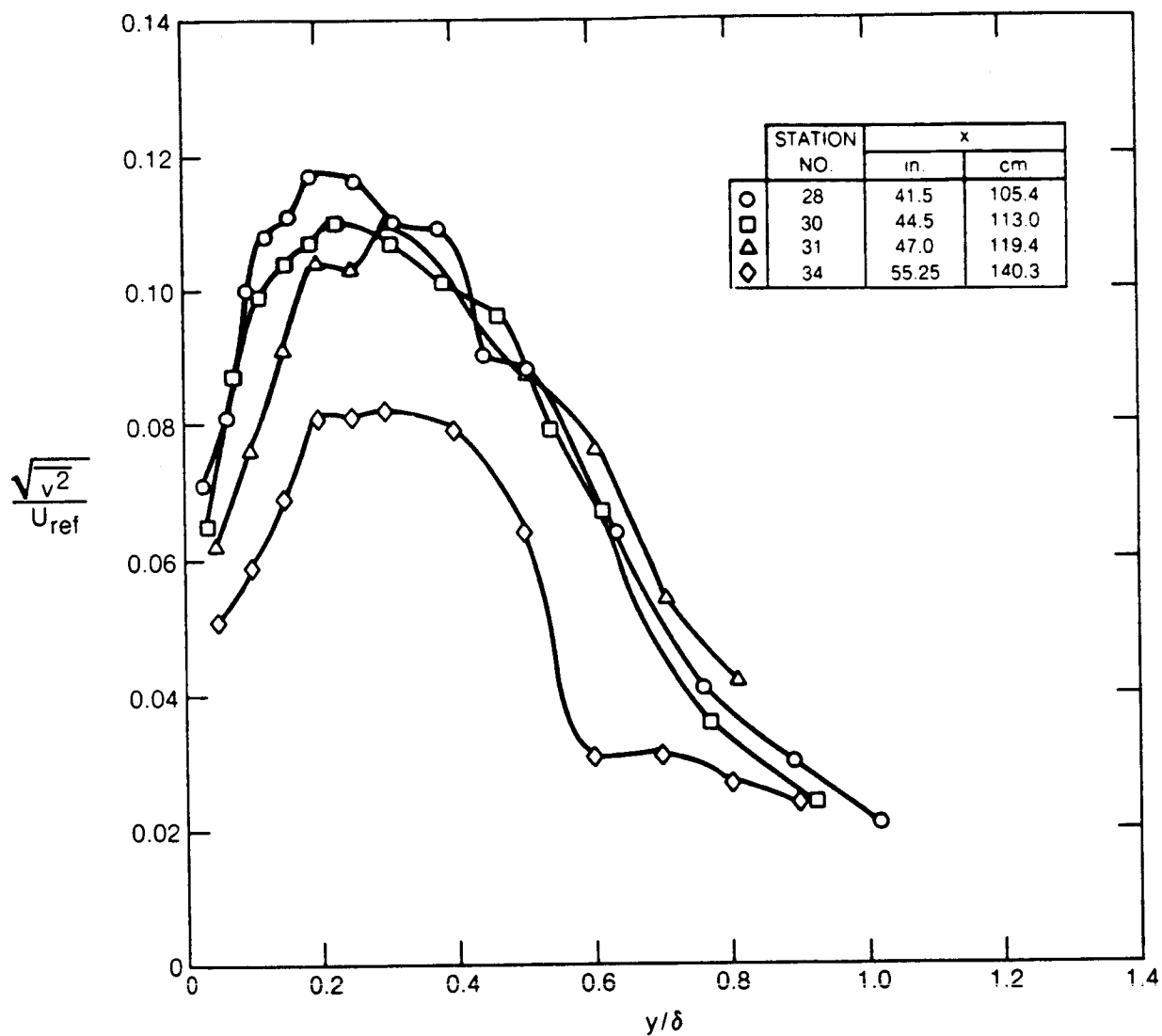


Figure 4-19d Non – Dimensional Transverse Turbulence Profiles (Concluded)

84-8-1-70

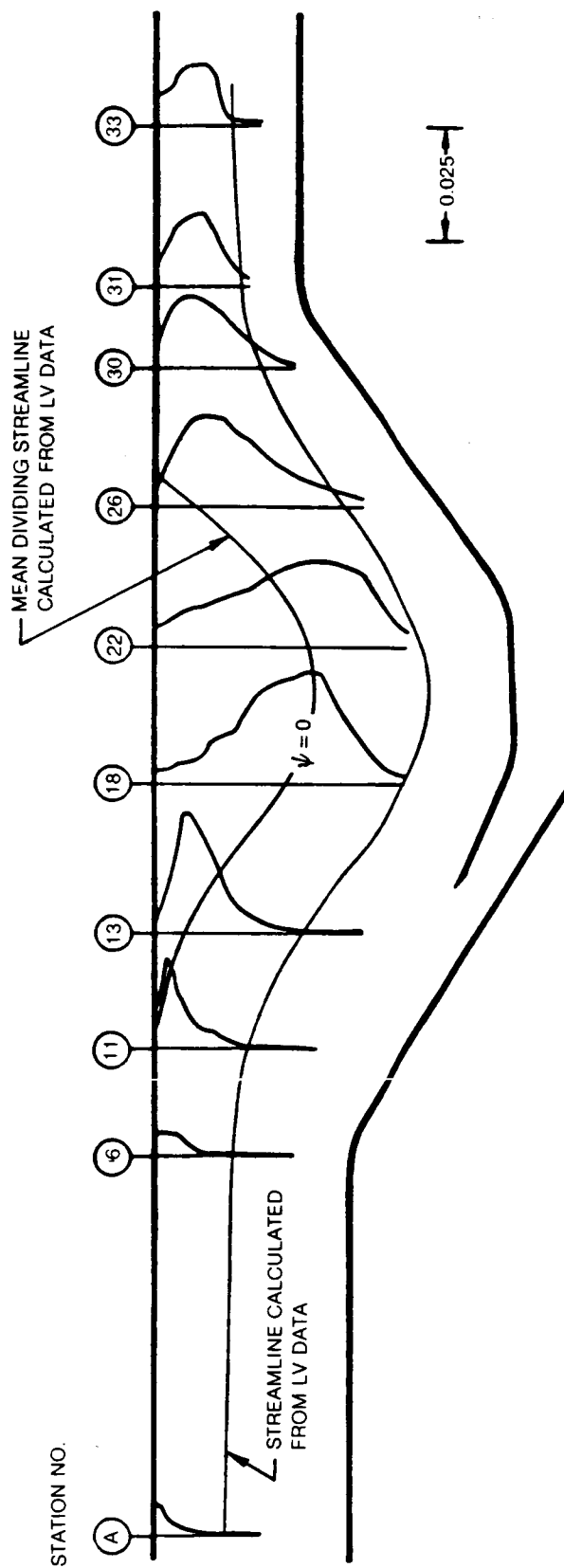
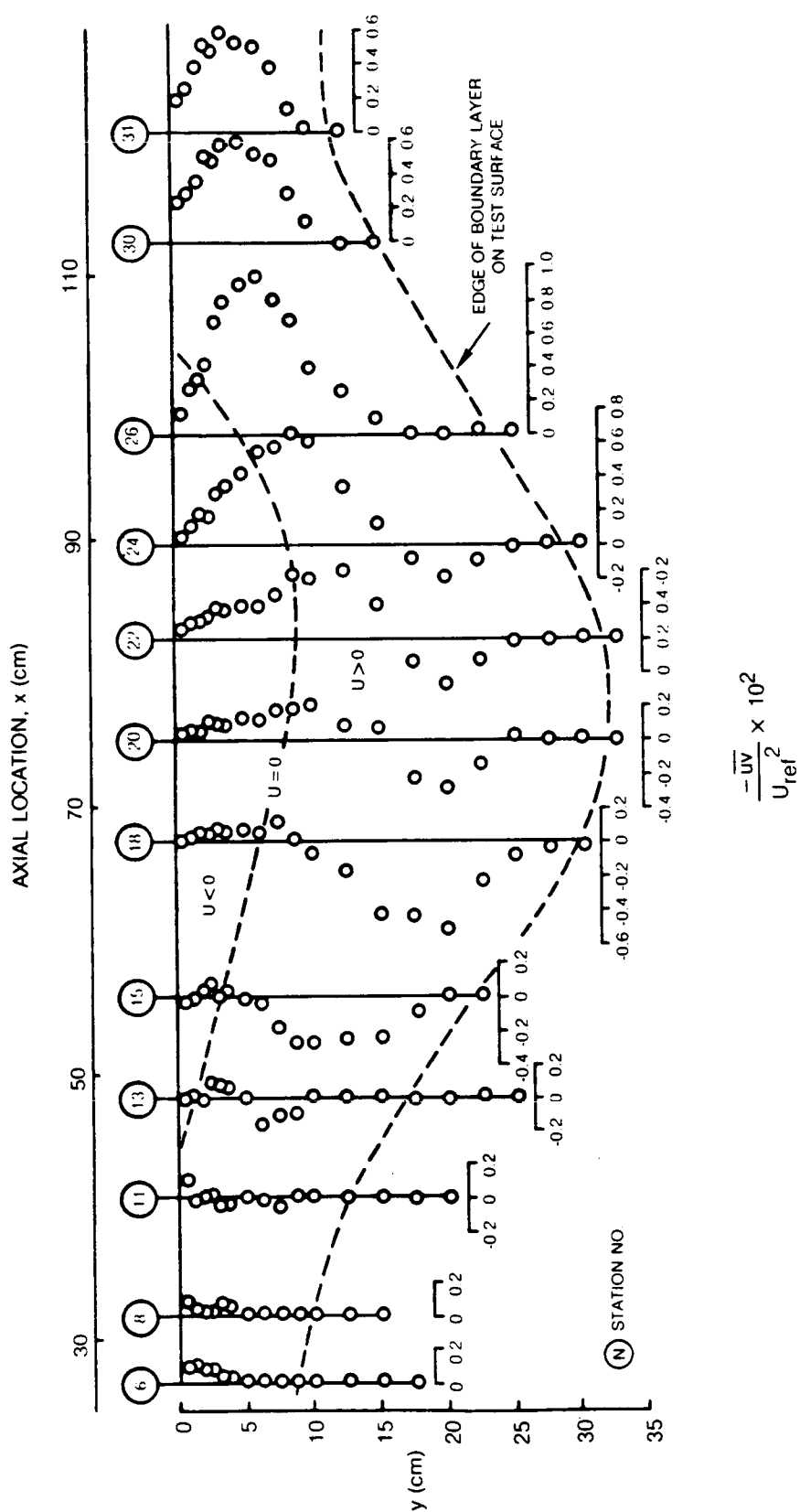


Figure 4-20 Profiles of Non-Dimensional Turbulence Kinetic Energy, y vs $\frac{(u^2 + 2v^2)}{2U_{ref}^2}$



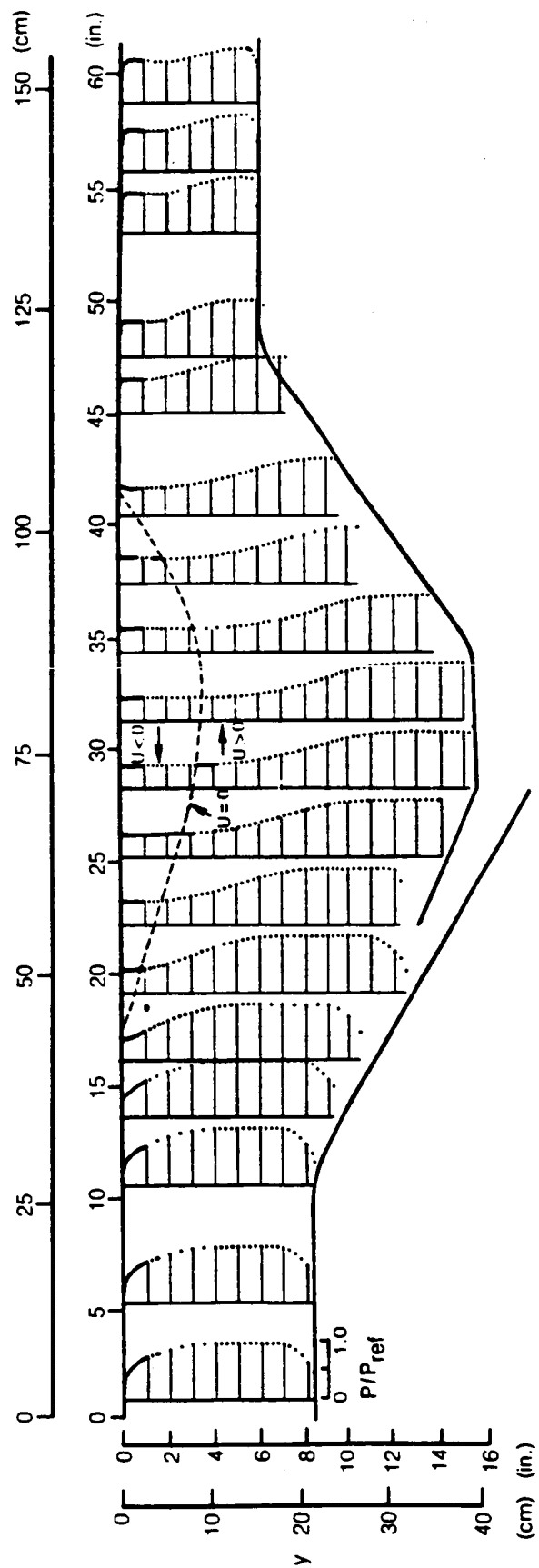
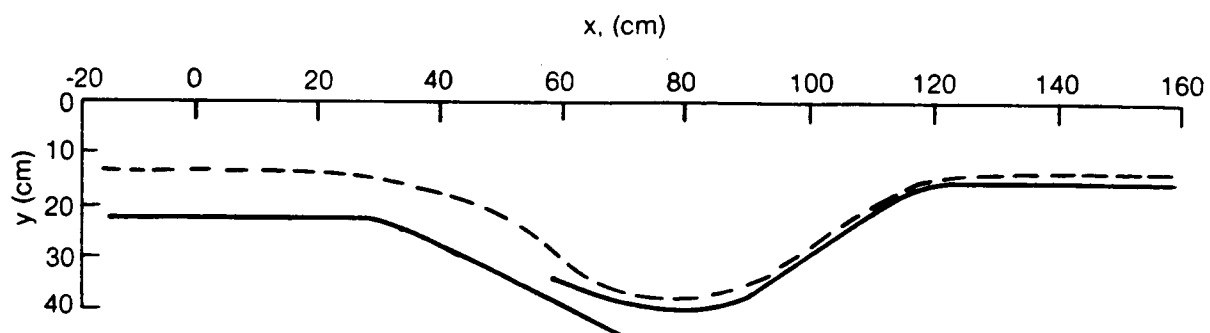


Figure 4-22 Normalized Total Pressure Profiles on Wind Tunnel Centerline



STATION NO	X (cm)	y (cm)
1L	-22.86	13.08
2L	2.54	13.34
3L	7.62	13.46
4L	13.34	13.56
5L	17.78	13.69
6L	37.62	17.58
7L	47.52	21.95
8L	57.63	28.35
9L	58.85	32.74
10L	69.62	37.57
11L	75.57	38.02
12L	82.55	37.34
13L	92.96	34.06
14L	98.43	30.05
15L	106.40	24.69
16L	111.51	21.54
17L	133.99	14.71
18L	140.97	14.76
19L	146.05	14.76
20L	151.13	14.73

Figure 4-23 Bounding Streamline Determined by Lower Wall Total Pressure Traverses

84-8-1-17

CHAPTER 5

ANALYSIS AND DISCUSSION

Chapter 4 presented the results from direct measurements along with their discussion. In this chapter, additional quantities derived from the measurements will be analyzed and discussed. These quantities include flowfield streamline coordinates, static pressure, skin friction, and streamwise shear stresses. Boundary layer integral properties and law-of-the-wall plots are also presented. The measured and derived data are then analyzed and compared to the results and correlations developed in previous investigations. In doing this the flowfield has been partitioned into eight regions or zones because the flat plate separated and reattached boundary layer has not been studied previously in its entirety with LV. Data in each flow zone will be compared to available data obtained in other separation and reattachment studies.

5.1 Flow Zones

The flow zones are defined in figure 5-1. Zone I is the attached boundary layer upstream of separation. Boundary layer profiles in Zone I can be compared to studies concerning the development of turbulent boundary layers in adverse pressure gradients. The attached boundary layer flows against the adverse pressure gradient until the kinetic energy in the boundary layer at the wall is converted into potential energy at which point the boundary layer separates from the test surface. Since the boundary layer kinetic energy at any point in a turbulent boundary layer is proportional to the square of the sum of the steady velocity field and the unsteady turbulence velocity field, separation occurs over a zone rather than at a point as occurs in a laminar boundary layer. The intermittent separation zone, Zone II, has been studied extensively for open separation bubbles by Sandborn, Kline, Simpson, and many others. Hence, comparisons can also be made for this region of the flowfield. Zone III, the turbulent separation bubble, is defined as the region between the mean dividing streamline and the test surface. Strong backflows exceeding 30 percent of the local freestream velocity occur within this region. The open separated flow data of Simpson et al. can be used as a basis for comparison in the upstream half of the bubble and the downstream half of the bubble can be compared to separation data obtained downstream of a backward facing step. The strong recirculating flow within the separation bubble causes a backflow boundary layer, Zone IIIA, to originate near the reattachment point and to develop along the test surface. No basis for comparison exists in this zone because details of the backflow boundary layer in a closed separation bubble have not been previously reported.

The reattachment of the separated shear layer is an inherently unsteady process which occurs within Zone IV, the reattachment zone, on the test surface. In this zone the reattaching flow impinges steeply onto the test surface causing a static pressure peak which drives the strong backflow within the separation bubble. The flow is characterized by high turbulence levels and frequent flow reversals. Boundary layer integral properties, skin friction, and forward flow fraction data in the reattachment zone can be compared to the data of Driver and Seegmiller (ref. 14), Westphal et al. (ref. 17), and others for reattaching flows behind a backward facing step.

Downstream of reattachment the flow recovers the structure of a flat-plate turbulent boundary layer. This process occurs in two stages. In Zone V, a new boundary layer begins to grow along the test surface and quickly develops a log-linear velocity profile near the wall. The relaxation of the outer free shear layer in Zone VI occurs much more slowly, however. Through a complicated process of turbulence energy exchange between Zones V and VI the turbulence structure downstream of reattachment gradually obtains the outer wake-like structure of a turbulent boundary layer. Data in Zones V and VI have been correlated with the recovering boundary layer profiles of Chandrsuda and Bradshaw (ref. 18).

When properly normalized the axial velocity profiles in Zone VII, the outer flow region, are found to be invariant throughout the test section. Results in this zone can be compared to separated flow studies of Perry and Fairlie (ref. 5) and Paterson and Weingold (ref. 36).

5.2 Static Pressure Field

The static pressure field within the test section was calculated at 36 stations. Twenty-six of the stations were located on the test plate centerline and five pairs of stations were located at ± 15.2 cm off the centerline. The measured quantities used to determine the static pressure, p , were the total pressure, P , and the mean axial and transverse velocities measured with the LV system

$$\frac{P - p_{w_{\text{ref}}}}{Q_{\text{ref}}} = \frac{P}{Q_{\text{ref}}(P)} - \frac{1}{2} \left[\left(\frac{U}{U_{\text{ref}}(U)} \right)^2 + \left(\frac{V}{U_{\text{ref}}(V)} \right)^2 \right] \quad (5-1)$$

where $Q_{\text{ref}}(P)$ is the dynamic pressure at the reference location during the measurement of P and $U_{\text{ref}}(U)$ and $U_{\text{ref}}(V)$ are the freestream velocities at the reference location during the measurement of U and V , respectively. As noted in Section 4.1, U_{ref} was adjusted during testing to maintain constant unit

Reynolds number at the reference location. The results are presented in terms of the difference between the local static pressure and the static pressure at the reference location in the boundary layer development section, $p_{w_{ref}}$, normalized by the reference dynamic pressure, Q_{ref} . For these calculations the density, ρ , which varied less than 0.3 percent throughout the test section, was assumed to be constant. Calculated values of the static pressure are listed in Table IV. Static pressure profiles at 15 stations on the test plate centerline are plotted in figure 5-2.

The transverse static pressure gradient, $\partial p / \partial y$, was essentially zero at the inlet and outlet stations. It was negative between Stations 3 and 15 due to streamline curvature. Within the separation bubble (Zone III) the static pressure was nearly constant except at the wall near reattachment (as shown previously in fig. 4-7) where the static pressure increased due to flow impingement onto the test surface. Outside the separation bubble between Stations 18 and 24, $\partial p / \partial y > 0$ due to the concave curvature of the streamlines in the freestream flow associated with flow around the bubble and the converging lower surface. Between Stations 30 and 33 the convex curvature of the lower surface at Station 31 caused $\partial p / \partial y < 0$ as the flow accelerated into the outlet duct.

The normal static pressure gradients within the test section were significant. At some stations the static pressure difference between the upper test surface and the lower wall equaled $0.5 Q_{ref}$. The static pressure gradients were caused by the streamline curvature in the inviscid flow due to the combined effects of the tunnel geometry and the aerodynamic blockage induced by the large separation bubble. The effect of the transverse static pressure gradients on the calculation of the boundary layer integral properties is assessed below in Section 5.3.3.

Spanwise variations in the static pressure were minimal at most stations. The maximum variation in static pressure between the centerline and the off-centerline traverse stations, which occurred near the boundary layer scoop and at Station 34 downstream of reattachment, was less than $.01 Q_{ref}/cm$.

5.3 Mean Flowfield Characteristics

5.3.1 Mean Flowfield Streamlines

Axial velocity profiles measured with the laser velocimeter were integrated to determine the value of the streamfunction ψ_i at any point y_i

$$\psi_i = \int_0^{y_i} U dy \quad (5-2)$$

The locus of points of equal values of ψ_i , determined by interpolation, were used to define the mean flowfield streamline pattern shown in figure 5-3. Coordinates for the mean dividing streamline and eight additional streamlines located 1.27 cm apart at initial LV measurement Station 6 are listed in Table VI. The bounding streamline (dashed line) determined from lower wall total pressure traverses (see Section 4.9.1) has also been plotted in figure 5-3. Coordinates of the bounding streamline are given in figure 4-23 for use in computing the flowfield. The displacement of the mean flowfield by the separation bubble is quite evident. The maximum thickness of the separation bubble, h , measured from the surface to the $\psi = 0$ mean dividing streamline was 17 cm (6.7 in.) as noted in Table VI. Separation bubble length was 64 cm (25 in.). Significant streamline curvature is evident in the vicinity of the separation bubble.

At most points within the test section the mean flowfield streamlines are tangent to the measured mean velocity vectors as expected in a steady flow. Nontangency between the streamlines and the mean flow vectors near the leading edge of the separation bubble is unexplained but may arise from individual realization bias errors (ref. 37) in the transverse velocity component measurements in regions of the flowfield having spatially non-uniform seed particle distributions. Such non-uniformities are noticeable near the separation bubble where the seed density in the shear layer around the bubble was higher than the density within the bubble. Thus, positive, downward velocity fluctuations would provide relatively fewer valid counts than negative, upward velocity fluctuations because of the lower seed density near the test surface. This individual realization bias would tend to reduce the magnitude of the measured transverse velocity component.

5.3.2 Inviscid Outer Flow

Analysis of mean velocity data acquired in the present experiments has shown a feature of the velocity profile development which appears to have important implications for the numerical modeling of the flow. When static pressure variations associated with streamline curvature are taken into account, congruence of velocity profiles outside of the recirculating region is found over the axial extent of the separation bubble region. This feature will be discussed in this section.

Axial velocity profiles measured on the test section with the laser velocimeter have been shown in figure 4-9. When the profiles from the various axial measurement stations are overlaid, station-to-station similarity is not

evident. Because of the large displacement of the flow streamlines caused by the separation bubble, the axial velocity profiles have been distorted by streamline curvature in addition to viscous effects.

It is possible, however, to separate viscous from streamline curvature effects by normalizing the measured axial velocity component, U , by the inviscid axial velocity component, U_i , at each point on the profile. The inviscid axial velocity component was calculated from the freestream total pressure, P_{ref} , the measured transverse velocity component, $V(y)$, and the local static pressure, $p(y)$, discussed in the previous section.

$$U_i(y) = \frac{2}{\rho} \sqrt{P_{ref} - p(y) - \frac{1}{2} \rho V^2(y)} \quad (5-3)$$

This procedure for normalizing the axial velocity profiles by the local inviscid velocity has been used previously by others to calculate boundary layer integral properties in flows over curved surfaces and in shock boundary layer induced separations where normal pressure gradients are also significant (see Section 5.3.3.1 "Definition of Integral Properties").

The normalized axial velocity profiles are shown in figure 5-4. These profiles have been overlayed in figure 5-5 using $y-\delta$ as the ordinate where y is the vertical distance from the flat plate test surface and δ is the local boundary layer thickness. For clarity, profiles at stations 18, 20, 22 and 26 have been omitted from figure 5-5 although their profiles lie within the envelope formed by profiles at stations 16, 24, and 28. Using the boundary layer at station 6 ($x = 26.7$ cm, 10.5 in.) as reference, it can be seen that as the flow moves downstream the inner part of the initial boundary layer profile is eroded by the viscous processes associated with separation and reattachment. A similar observation has recently been made in a widely different separated flow experiment. As reported by Paterson and Weingold (ref. 36), flow downstream of a simulated compressor airfoil blunt trailing edge displays velocity profile congruence over the axial extent of the trailing edge separation bubble. In that case profile similarity was directly evident in the measured data since streamline curvature and associated static pressure gradients were significantly less than that encountered in the present experiment.

These results suggest that the outer flow can be considered basically an inviscid, rotational flow which convects around the viscously dominated recirculation zone. This is considered to be potentially important in the modeling of separated flow by viscous-inviscid interaction procedures.

5.3.3 Boundary Layer Integral Properties

5.3.3.1 Definitions of Integral Properties

In classical boundary layer theory in which the static pressure is assumed to be constant across the boundary layer, the displacement thickness, δ^* , and the momentum thickness, θ , are defined with the boundary layer edge velocity as the reference velocity

$$\delta_1^* = \int_0^{\delta} \left(1 - \frac{\rho U}{\rho_e U_e} \right) dy \quad (5-4)$$

$$\theta_1 = \int_0^{\delta} \frac{\rho U}{\rho_e U_e} \left(1 - \frac{\rho U}{\rho_e U_e} \right) dy \quad (5-5)$$

As long as the boundary layer thickness to the streamline radius of curvature is less than about 1 percent, the static pressure difference across the boundary layer will be less than 2 percent of the dynamic pressure and these definitions are adequate (ref. 38). However, in the present experiment, as noted above, streamline curvature within the test section was significant. Static pressure changes across the boundary layer exceeding 40 percent of the dynamic head occurred at several measurement stations in the vicinity of the separation bubble.

Kiock (ref. 38) has considered the interpretation of boundary layer data when sizeable transverse pressure gradients exist across the boundary layer. He reviewed five definitions for both the displacement and momentum thickness and compared their calculated values in example flows having prescribed normal static pressure gradients. In the present experiment, boundary layer integral properties have been calculated from data using three of the five definitions reviewed by Kiock.

The displacement thickness is defined as the thickness of the hypothetical layer in which the fictitious inviscid flow is equal to the reduction of the real mass flow due to the boundary layer. Since the mass flux between the displacement surface and the edge of the boundary layer in the fictitious inviscid flow must equal the total mass flow in the real boundary layer, the displacement thickness in the current experiment can be defined by the following equation

$$\int_{\delta^*}^{\delta} U_i dy = \int_0^{\delta} U dy \quad (5-6)$$

where U_i is the local inviscid axial velocity defined above in Section 5.3.2.

Kooi (ref. 39) has shown that equation (5-6) can be solved to obtain the true definition of δ^* in the presence of normal static pressure gradients as the sum of the displacement thickness evaluated from classical boundary layer theory, δ_1^* , and a correction term to account for the effects of normal static pressure gradients

$$\delta_2^* = \int_0^{\delta} \left(1 - \frac{U}{U_{iw}} \right) dy - \int_0^{\delta} \left(1 - \frac{U_i}{U_{iw}} \right) dy \quad (5-7)$$

where U_{iw} , the inviscid velocity at the wall calculated from the local wall static pressure and the inlet total pressure, equals U_e when $\partial p / \partial y = 0$.

Another definition of the displacement thickness, referred to by Kiock (ref. 38) as the "pressure-based" displacement thickness,

$$\delta_3^* = \int_0^{\delta} \left(1 - \frac{U}{U_i} \right) dy \quad (5-8)$$

has been used by So and Mellor (ref. 40), Mayle, et al. (ref. 41), and others to account for normal static pressure gradients due to streamline curvature.

Kooi has shown that the true definition of the momentum thickness can be expressed as the sum of the momentum thickness evaluated from classical boundary layer theory, θ_1 , and a correction term to account for the effects of the normal static pressure gradients.

$$\theta_2 = \int_0^{\delta} \frac{U}{U_{iw}} \left(1 - \frac{U}{U_{iw}} \right) dy - \int_0^{\delta} \frac{U_i}{U_{iw}} \left(1 - \frac{U_i}{U_{iw}} \right) dy \quad (5-9)$$

The "pressure-based" momentum thickness for incompressible flow has been defined (ref. 38) as

$$\theta_3 = \int_0^{\delta} \frac{U}{U_i} \left(1 - \frac{U}{U_i} \right) dy \quad (5-10)$$

The boundary layer shape factor, H , defined as the ratio between the displacement thickness and the momentum thickness can be calculated for each of the three definitions of the integral properties defined above.

Kiock (ref. 38) used examples to show that when U_i increases monotonically across the boundary layer $\delta_2^* > \delta_3^* > \delta_1^*$, $\theta_2 > \theta_3 > \theta_1$, and $H_2 < H_3 < H_1$. When U_i decreases monotonically across the boundary layer $\delta_2^* < \delta_3^* < \delta_1^*$, $\theta_2 < \theta_3 < \theta_1$, and $H_2 > H_3 > H_1$. The equations of classical theory hold when U_i is constant across the boundary layer and $\delta_1^* = \delta_2^* = \delta_3^*$, $\theta_1 = \theta_2 = \theta_3$ and $H_1 = H_2 = H_3$.

5.3.3.2 Calculated Values of Integral Properties

Each of the three values of the displacement thickness, momentum thickness, and the shape factor defined above were calculated at each LV traverse location within the test section. Plotted values of the displacement and momentum thicknesses on the wind tunnel centerline are shown in figure 5-6a. The displacement thickness increased rapidly downstream of the start of the intermittent separation zone ($x = 40.6$ cm, 16 in) until it peaked at $x = 74.9$ cm (29.5 in.), the location of the maximum thickness of the separation bubble (see fig. 5-3). The shape of the displacement thickness curve is almost symmetric about the center of the bubble. The momentum thickness increased much more slowly as the boundary layer approached separation. Within the separation bubble the momentum thickness remained relatively constant before decreasing downstream of reattachment.

Values of the shape factor are plotted in figure 5-6b. The true value of the shape factor, H_2 , increased from 1.38 at $x = 26.7$ cm (10.5 in.) to 2.09 at $x = 40.6$ cm (16.0 in.) near separation, then to a peak value of 16.1 at $x = 74.9$ cm (29.5 in.) before declining to a value of 1.23 in. the accelerating flow in the outlet duct. Peak values of H_3 and H_1 also occurred at $x = 74.9$ cm and equaled 11.8 and 7.5 respectively.

The results follow the trends shown in Kiock's example boundary layers. Upstream of separation ($x < 48$ cm, 19 in.) and downstream of reattachment ($x > 113$ cm, 44.5 in.), where $\partial U_i / \partial y > 0$ across the boundary layer, $\delta_2^* < \delta_3^* < \delta_1^*$, $\theta_2 < \theta_3 < \theta_1$ and $H_2 > H_3 > H_1$. Near the center of the separation bubble (48 cm $< x < 90$ cm), $\partial U_i / \partial y < 0$ across the boundary layer and $\delta_2^* < \delta_3^* < \delta_1^*$, $\theta_2 < \theta_3 < \theta_1$, and $H_2 > H_3 > H_1$. At $x = 48$ cm, 19 in., $\partial U_i / \partial y \approx 0$ across the boundary layer and $\delta_1^* = \delta_2^* = \delta_3^*$, $\theta_1 = \theta_2 = \theta_3$, and $H_1 = H_2 = H_3$. At the

remaining measurement stations the sign of $\partial U_i / \partial y$ varied across the boundary layer. Although Kiock demonstrated the relationships between classical, true, and pressure-based integral parameters with simple mathematical models of the boundary layer, the agreement shown here demonstrates that these trends hold equally well in complex flowfields of interest.

5.3.4 Skin Friction Coefficient on Test Surface

Law-of-the-wall velocity profiles were calculated from pitot data and LV velocity data in the attached flow upstream of separation and downstream of reattachment. The skin friction coefficient was determined from the friction velocity, U_τ

$$C_f = 2 \frac{U_\tau^2}{U_{ref}^2} \quad (5-11)$$

Within the separation bubble the skin friction coefficient was determined from backward facing pitot data. At all stations within the bubble C_f was evaluated from the normal velocity gradient at the wall estimated from pitot data. Where possible C_f was also calculated from friction velocities obtained from law-of-the-wall plots of the backflow velocity profiles. Details of the calculations are given in Section 5.5.1.

The skin friction coefficients in the test section are presented in terms of the upstream reference velocity (i.e., $C_f = 2\tau_w / \rho U_{ref}^2$) and also in terms of the local freestream velocity (i.e., $C_{f_L} = 2\tau_w / \rho U_e^2$). Values of the skin friction coefficient based upon the upstream reference velocity, C_f , will be used to quantify wall shear stress variations in the test section. C_{f_L} , based on the local freestream velocity, will be used to compare to Swafford's correlation of skin friction in attached and separated turbulent boundary layers (ref. 42).

Values of C_f on the test plate centerline are plotted in figure 5-7a. At the reference station 24 cm upstream of the test section inlet C_f equaled 0.00267, a typical value for a zero-pressure gradient turbulent boundary layer having $Re_\theta = 11,100$. C_f decreased in the decelerating boundary layer upstream of separation until it reached a value of 0.0001 at $x = 40.6$ cm just upstream of detachment. The negative value of C_f calculated from the backflow velocity profiles within the separation bubble indicated that the wall shear stress within the separation bubble was approximately 1/10 as large as the wall shear in the attached flow wall upstream of separation. Down-

stream of reattachment C_f increased rapidly until a value of 0.00282 was reached at the last measurement station in the exit duct.

Swafford (ref. 42) has proposed the following empirical correlation which uses measured values of shape factor, H , and momentum thickness Reynolds number, Re_θ , to estimate C_{f_L} in both attached and separated flows.

$$C_{f_L} = \frac{0.3e^{-1.33H}}{(\log_{10} Re_\theta)^{1.74+.31H}} + (1.1 \times 10^{-4}) \left[\tanh \left(4 - \frac{H}{.875} \right) - 1 \right] \quad (5-12)$$

The first term in Swafford's correlation is the skin friction correlation given by White (ref. 43) for attached turbulent boundary layers. Swafford added the second term to correlate the negative skin friction coefficients in reversed flows. Experimentally determined values of C_{f_L} on the test plate centerline have been plotted in figure 5-7b together with Swafford's correlation. Experimentally determined values of θ_2 and H_2 were used to evaluate eq. (5-12). The agreement between the correlation and the data is very good up to separation. The correlation correctly predicts the length of the separation bubble but significantly underpredicts the skin friction in the backflow boundary layer. The maximum negative value of skin friction coefficient (i.e., $C_{f_L} = -0.00022$) which can be obtained from eq. (5-12) limits its ability to correlate the wall shear in energetic backflow boundary layers. Downstream of reattachment the Swafford correlation underpredicts the rapid monotonic increase in skin friction by 20 to 40 percent. Swafford anticipated that his correlation would not be universally applicable to all flow situations since it was developed largely from the open separation bubble data of Simpson et al. (ref. 1) and Alber et al. (ref. 44). The Swafford correlation has not been compared previously to separation bubble data through reattachment.

5.3.5 Demonstration of Flow Two-Dimensionality

The criterion to measure the spanwise uniformity of the flow at the initial measurement plane, test section inlet, just upstream of separation, and within the reversed flow region have been defined in Section 3.2.4 "Flow Two-Dimensionality and Steadiness Criteria". The attainment of the spanwise uniformity criterion at the initial measurement plane, which was defined as deviation of less than one percent in the measured pitot pressure at tunnel midheight, has been described in Section 4.2 "Initial Plane Boundary Conditions". The attainment of a straight separation line which deviated from a line perpendicular to the tunnel centerline by ± 6 percent of the test section span excluding the sidewall regions has been described in Section 4.3 "Flow

Visualization". This ± 6 percent deviation only slightly exceeded the ± 5 percent criterion. Satisfaction of the remaining criterion that the boundary layer momentum thickness at each spanwise measurement station (i.e., $z = -15.2$ cm, 0, $+15.2$ cm) deviate from the spanwise average by less than 5 percent will be discussed in this section.

First, however, the spanwise uniformity of the total pressure profiles within the test section should be noted. In figure 5-8 nondimensionalized total pressure data are plotted vs. transverse distance from the test plate at three spanwise locations for each of six axial stations: two stations upstream of separation, two stations within the separation bubble, two stations downstream of reattachment. The profiles at Stations 2, 11, 18, and 24, encompassing the region from upstream of separation to the aft end of the bubble, show good spanwise uniformity with the maximum profile difference being on the order of $.05 P/Q_{ref}$. Downstream of reattachment at Station 31 (fig. 5-8e) the total pressure profile on the centerline has a larger defect at $2.5 \text{ cm} < y < 7.5 \text{ cm}$ than the off-centerline profiles. This difference is almost eliminated at Station 34 (fig. 5-8f) in the exit duct.

The same data have been replotted in figure 5-9 with the ordinate normalized by the boundary layer thickness. Minimal spanwise skewness is evident in the profiles at Stations 18 (fig. 5-9c) and 24 (fig. 5-9d) indicating that the skewness observed in figure 5-8c and 5-8d resulted from small spanwise variations in the boundary layer thickness within the separation bubble. The variation in the boundary layer thicknesses measured at the $z = +15.2$ cm and $z = -15.2$ cm locations at stations 18 and 24 were 11.6 percent and 7.0 percent of the boundary layer thicknesses on the centerline, respectively.

The spanwise variations in the momentum thickness at the same six axial stations has been assessed. Values of θ_1 , the momentum thickness derived from classical boundary layer theory, and θ_3 , the pressure-based momentum thickness (see Section 5.3.3.1 "Definitions of Integral Properties") normalized by the spanwise average are plotted in figure 5-10. At stations 2 and 11 upstream of separation and Stations 18 and 24 within the reversed flow region θ_1 varied less than 5 percent across the span. Downstream of reattachment at stations 31 and 34 the momentum thickness peaked on the wind-tunnel centerline and varied from the spanwise average by 8 and 13 percent, respectively. The pressure-based momentum thickness, θ_3 , showed similar trends to θ_1 except at station 18 where θ_3 was 8 percent less than the spanwise average at $z = 0$. The slight three-dimensionality in the flowfield downstream of reattachment, apparent from the spanwise variations in momentum thickness, is consistent with the inward skewness of the surface tufts shown above in figure 4-4.

5.4 Description of the Separation Process

5.4.1 Nature of the Decelerating Boundary Layer

The streamwise mean-velocity distribution in a turbulent boundary layer can be expressed as a linear combination of wall and wake functions as shown by Coles (ref. 45).

$$u^+ = f(y^+) + \frac{\Pi}{\kappa} w\left(\frac{y}{\delta}\right) \quad (5-13)$$

where κ is a constant to be determined from experimental data and $w(y/\delta)$ is a universal wake function. The near wall flow is dominated by viscosity whereas the wake flow represents the cumulative effect of the pressure gradient. When the inner layer (or wall) structure is in equilibrium with the outer layer (or wake) structure the turbulent boundary layer is said to be in equilibrium.

Coles showed that the wake parameter Π could be expressed as

$$\Pi = \kappa \left(\frac{\delta^*}{\delta} \right) \left(\frac{U_e}{U_\tau} \right) - 1 \quad (5-14)$$

He further noted that when Π is constant the turbulent boundary layer is in equilibrium and there is a certain balance between the constraints imposed by inertia (i.e. U_e) and viscosity (i.e. U_τ). A balance also exists between the large-scale and small-scale mixing processes (ref. 45). This concept of equilibrium is useful in zero, favorable, and slightly adverse pressure-gradient, turbulent boundary layer flows whose mean-velocity profile and turbulence structure are dominated by the effects of the wall (ref. 6).

Another equilibrium parameter, which characterized the flow in the outer layer, was derived by Clauser (ref. 46).

$$\beta = \frac{\delta^*}{\tau_w} \frac{dp_e}{dx} \quad (5-15)$$

Clauser showed that a turbulent boundary layer with variable pressure gradient, but β constant, is in equilibrium.

White (ref. 43) studied 13 near equilibrium flows presented at the 1968 Stanford Conference (ref. 47) and proposed the following empirical relationship between Π and β for equilibrium flows

$$\Pi = 0.8 (\beta + 0.5)^{0.75} \quad (5-16)$$

To determine the nature of the boundary layer upstream of separation, velocity profiles were plotted in law-of-the-wall coordinates (fig. 5-11). The velocity profiles at Stations 0-5, were determined from pitot traverses with the assumption that transverse static pressure gradients were negligible. At Station 6 ($x = 26.25$ cm) profiles were determined from both pitot and LV data. Only LV data is presented at Station 8 ($x = 31.75$ cm) because of significant transverse static pressure gradients at that station.

Values of skin friction, C_f , and the wake parameter, Π , were calculated at each station from the profiles. The skin friction decreased monotonically from a value of .00267 at Station 0 ($x = -24.1$ cm) to .00077 at Station 8. The wake parameter, Π , equaled 0.33 at Station 0 where the boundary layer was nearly in equilibrium (see Section 4.2). (Coles suggested a value of 0.55 for a flat-plate zero-pressure-gradient boundary layer.) The wake parameter remained relatively constant through Station 3 ($x = 13.34$ cm) before increasing rapidly to a value of 3.4 at Station 8 ($x = 31.75$ cm) as the flow encountered an increasingly adverse pressure gradient as shown previously in figure 4-7.

The Clauser equilibrium parameter, β , was also evaluated at the same measurement stations after eq. (5-15) was transformed into the following form.

$$\beta = \frac{\delta^*}{C_f} \frac{dC_p}{dx} \quad (5-17)$$

The calculated values of β and Π are plotted in figure 5-12 together with the empirical curve, eq. (5-16), defining the relationship between Π and β for equilibrium flows. As shown in the figure, although the boundary layer was nearly in equilibrium at Stations 0, 1 and 2, neither Π nor β remained constant between Sections 3 and 8 as the boundary layer lost its equilibrium structure when it encountered the strong adverse pressure gradient.

Some insight into the reasons for this loss of equilibrium can be obtained by differentiating eq. (5-17) with respect to x

$$\frac{\partial \beta}{\partial x} = \frac{\delta^*}{C_f} \frac{\partial^2 C_p}{\partial x^2} + \frac{1}{C_f} \frac{\partial C_p}{\partial x} \frac{\partial \delta^*}{\partial x} - \frac{\delta^*}{C_f^2} \frac{\partial C_p}{\partial x} \frac{\partial C_f}{\partial x} \quad (5-18)$$

Thus, it should not be surprising that given the shape of the measured static pressure distribution upstream of separation (i.e. $\partial^2 C_p / \partial x^2 > 0$) that the decelerating flow was not in equilibrium. Since $\partial \delta^* / \partial x > 0$ and $\partial C_f / \partial x < 0$ upstream of separation, all the terms on the rhs of eq. (5-18) are positive, thereby precluding $\partial \beta / \partial x$ from equaling zero, the condition for equilibrium. In decelerating flows, equilibrium can only be achieved when $\partial^2 C_p / \partial x^2 < 0$.

Cutler and Johnston (ref. 6) have noted that in strongly adverse pressure gradient and detaching flows the concept of equilibrium is not too useful. The boundary layer loses profile and structural self-similarity when the inner layer cannot adjust fast enough to changes imposed on the outer layer by the adverse pressure gradient.

A measure of the strength of the gradient can be obtained from a ratio of the boundary layer thickness, δ , and a characteristic length scale of the adverse gradient, $U_e / (\partial U_e / \partial x)$.

$$R = \frac{\delta}{U_e} \frac{\partial U_e}{\partial x} \quad (5-19)$$

This non-dimensional gradient strength, R , usually can be calculated from experimental data when detailed profile information is not available to evaluate the wake parameter, Π . In the following section values of R have been calculated for the experiments of Simpson et al. (ref. 2) and Sandborn and Liu (ref. 49) and are compared to the non-dimensional gradient strengths calculated from data measured in the current study.

5.4.2 Analysis of Data in the Separation Region

In the absence of a salient edge, turbulent boundary layer separation occurs over a region rather than at a single streamwise location as occurs in laminar boundary layer separation. This process of turbulent boundary layer separation on a faired surface has been described by Sandborn and Kline (ref. 23) as follows:

"...separations of a turbulent shear layer do not usually begin in a steady or two-dimensional fashion on a faired surface. Instead they more often commence with intermittent streaks of backflow extremely near the surface. At the present time the onset of these streaks of backflow is not well correlated; indeed, the onset apparently depends on the nature of the fluctuations in the free stream. However, this is probably not of crucial importance, since these streaks of backflow are now known to be only an evidence of the existence of islands of hesitation which form a portion of the inherent flow model of the wall layers of the turbulent shear layer described by Kline and Runstadler (ref. 48). In favorable or mild adverse pressure gradients these islands of hesitation merely move more slowly than neighboring fluid layers; backflows are not observed. However, as the adverse pressure gradient is increased, these layers of very small inertia begin, relatively soon, to show upstream motions and to create local intermittent flow separation with streaks of backflow near the surface of a very small length scale. As the adverse pressure gradient is increased still further, these local backflows begin to accumulate slow moving fluid near the wall faster than it can be removed by the through flow. This leads to large transient three-dimensional stall patterns wherein the slow moving fluid is removed by intermittent adjustments in the over-all flow pattern and pressure distribution. Finally, upon still further increase in adverse pressure gradient, this process leads to a complete breakdown of the boundary-layer potential flow pattern and a fully established stall."

The following terminology has been defined (refs. 6 and 8) to quantify the process of turbulent boundary layer separation.

Detachment (D) - the locus of points where the limiting streamline of the time-averaged flow leaves the wall; a location of zero mean skin friction.

Incipient Detachment (ID) - the point upstream of detachment having backflow at the wall 1 percent of the time ($\gamma_{p_U} = 0.99$).

Intermittent Transitory Detachment (ITD) - the point upstream of detachment having 20 percent instantaneous backflow of the wall ($\gamma_{p_U} = 0.80$).

Transitory Detachment (TD) - the point in the region of detachment having 50 percent instantaneous backflow at the wall ($\gamma_{p_U} = 0.50$). This point is usually coincident with or very close to the detachment point (D).

The locations of incipient detachment, intermittent transitory detachment, and transitory detachment for the current study occurred at $x = 32$, 35.5 , and 42 cm, respectively, as shown in figure 5-13. Thus, the axial

extent of the separation region between incipient detachment and detachment was 10 cm which was less than the 11 cm thick boundary layer at Station 8 ($x = 31.75$ cm) just upstream of incipient detachment. Sandborn and Liu (ref. 49) who studied a turbulent separation bubble on a curved surface also achieved separation over one boundary layer thickness whereas Simpson et al separated the flow more gradually over 4.4 boundary layer thicknesses. Cutler and Johnston (ref. 6) did not achieve detachment and Smith et al (ref. 25) and Perry and Fairlie (ref. 5) did not measure the forward flow fraction.

To compare the forward flow fraction data in the separation region with data obtained by other investigators, γ_{p_u} has been plotted vs. a shape factor, $h = (H_2 - 1)/H_2$, in figure 5-14. The shaded region represents the range of turbulent boundary layer separation and reattachment data surveyed by Kline et al (ref. 50). All the turbulent separation cases surveyed were near equilibrium. The data obtained upstream of detachment in the current study lies outside and to the left of the envelope of the equilibrium separation data surveyed. Transitory detachment was achieved in the current study at $h = 0.55$, significantly less than the $0.69 < h < 0.77$ range of the surveyed data. This result could have occurred because of the nonequilibrium nature of the decelerating boundary layer in the current study. The strong adverse pressure gradient caused detachment to occur before the profile could adjust to an equilibrium shape.

Correlations have been developed in the $H-\Lambda$ plane, where $\Lambda = \delta^*/\delta$, to demarcate the regions of unseparated flow, intermittent separation, and fully developed separation. Sandborn (ref. 51) defined the line of demarcation between unseparated flow and intermittent separation in a turbulent boundary layer by the following equation

$$H = 1 + \frac{1}{1-\Lambda} \quad (5-20)$$

Sandborn and Kline (ref. 23) demonstrated that eq. (5-20) correlated all known intermittent separation data available at that time. Sandborn (ref. 51) also defined a line in the $H-\Lambda$ plane to denote the location of laminar boundary layer separation. Sandborn and Liu (ref. 49) later showed that the laminar separation line could be generalized as a zero wall shear separation line since it also demarcated the regions of intermittent and fully developed turbulent separation.

The correlations of Sandborn, the present experimental data, and the data of Simpson (ref. 1), Perry and Fairlie (ref. 5), Smith et al (ref. 25), and Sandborn and Liu (ref. 49), are shown in figure 5-15. Equations (5-7) and (5-9), which include the effects of normal static pressure gradients within the boundary layer, were used to determine the boundary layer integral

properties from the current experimental data. The Sandborn curves correlate the experimental data of both Simpson and the current experiment very well. In the current experiment, intermittent separation (ITD) commenced just upstream of Station 11 and separation (i.e. detachment (D)) occurred downstream of Station 13. The locus of data points from the present experiment also passes through the range of all experimental separation data surveyed by Sandborn. The location of intermittent and fully developed separation in Simpson's experiment were also predicted by the Sandborn correlation.

The data of Smith et al and Perry and Fairlie generally follow the trends of Simpson's data which lie to the right of the data obtained in the current study. The data of Sandborn and Liu show intermittent and fully developed separations occurring near the boundaries predicted by Sandborn's correlations. However, their data lie significantly to the left and outside the range of data surveyed by Sandborn and Kline.

Values of R , the non-dimensional strength of the deceleration gradient, were calculated at the point of incipient detachment and transitory detachment for the current experiment and for the studies of Simpson et al and Sandborn and Liu. At incipient detachment, R , was calculated using eq. (5-19) to be 0.022, 0.052 and 0.061, for the data of Simpson, the current study, and Sandborn and Liu, respectively. At detachment, the same relationship existed. R equaled 0.026, 0.033, and 0.097 for the data of Simpson, the current study, and Sandborn and Liu, respectively. Thus the deceleration gradient imposed by Sandborn and Liu was larger than the gradient imposed in the current study, which in turn was larger than Simpson's deceleration gradient. These data tend to indicate that increasing R causes the locus of data points in a given experiment to move up and to the left in figure 5-15. A consequence of this movement is that δ^*/δ at separation varies inversely with R .

Kline, Bardina, and Strawn (ref. 50) have developed an improved correlation for detachment for any boundary layer having a velocity profile which satisfies the modified Coles' wall-wake profile (ref. 30).

$$U^+ = \frac{1}{\kappa} \ln y^+ + \frac{\Pi(x)}{\kappa} \left(1 - \cos \frac{\pi y}{\delta} \right) + C \quad (5-21)$$

where $\Pi(x)$ is the wake amplitude. Equation (5-21) has been extremely effective in correlating the vast majority of turbulent boundary layers. The correlation becomes inadequate only for those boundary layers in which the inner and outer layers are far from equilibrium (ref. 50). Kline et al. cast eq. (5-21) into the following form

$$\frac{U}{U_{\infty}} = 1 + V_T \ln \left(\frac{y}{\delta} \right) - V_B \cos^2 \frac{\pi y}{2\delta} \quad (5-22)$$

where V_B (the nondimensional wake amplitude) and V_T (the dimensionless shear velocity) are defined as

$$V_B = 2U_{\tau} \Pi(x)/\kappa U_{\infty} \quad (5-23)$$

$$V_T = U_{\tau}/\kappa U_{\infty} \quad (5-24)$$

respectively. The shear velocity, U_{τ} , is defined to be positive in both attached and separated flows.

Using eqs. (5-4) and (5-5) to define the momentum and displacement thicknesses, eq. (5-22) can be integrated directly to yield

$$\frac{\theta}{\delta} = V_T + 0.5 V_B - 2V_T^2 - 1.5895 V_T V_B - .375 V_B^2 \quad (5-25)$$

$$\frac{\delta^*}{\delta} = V_T + 0.5 V_B \quad (5-26)$$

Solving eq. (5-26) for the wake strength, V_B , and substituting the result into eq. (5-25) yields the correlating equation

$$\frac{h}{\Lambda} = 1.5 + 0.179 \frac{V_T}{\Lambda} + 0.321 \frac{V_T^2}{\Lambda} \quad (5-27)$$

where

$$h = \frac{\delta^* - \theta}{\delta^*} = \frac{H - 1}{H} \quad (5-28)$$

$$\Lambda = \frac{\delta^*}{\delta} \quad (5-29)$$

For equilibrium boundary layers the dimensionless shear velocity, V_T , is given implicitly by

$$V_T = \frac{1 - 2\Lambda}{\ln \frac{|V_T|}{\Lambda} + \ln (\kappa Re_{\delta^*}) + 0.05} \quad (5-30)$$

The correlation of Kline et al. (eq. (5-27)) is plotted in figure 5-16 along with the data of Cutler and Johnston, Sandborn and Liu, and the present experiment. The shaded region represents the range of near-equilibrium separation data surveyed by Kline et al. The data obtained in the current study upstream of separation (i.e., Stations 6, 8, and 11) and in the upstream half of the separation bubble (i.e., Stations 13-15) lie near the Cutler and Johnston data above the Kline correlation for equilibrium turbulent boundary layers and near the boundary of the shaded region. The data of Sandborn and Liu, which was obtained in a strong adverse pressure gradient on a convex surface, lie significantly above the correlation line and outside the shaded region. Data obtained in the downstream half of the separation bubble (i.e., Stations 18, 20, 22, 24 and 26) and downstream of reattachment (i.e., Stations 28 and 31) lie on or near the Kline correlation.

Deviation of data obtained by Sandborn and Liu, Cutler and Johnston, and at Stations 6-15 in the current study from the correlation line is not surprising since the Kline correlation is restricted to the special case of equilibrium turbulent boundary layers. As discussed in Section 5.4.1 above, the decelerating boundary layer in the present experiment which was near equilibrium at the test section inlet lost its equilibrium structure when it encountered the strong adverse pressure gradient. To estimate the effect of boundary layer nonequilibrium on the Kline correlation, eq. (5-27) was rederived for a boundary layer having no wake component (i.e., $\Pi = V_B = 0$). For a zero-wake boundary layer eq. (5-27) becomes

$$h = 2\Lambda \quad (5-31)$$

As shown in figure 5-16 the data from Stations 6-15 generally lie between the equilibrium correlation (eq. (5-27)) and the zero-wake correlation (eq. (5-31)). As the flow moves downstream the data approaches the equilibrium correlation as the strength of the deceleration gradient diminishes. Note also in figure 5-16 that the Sandborn-Kline correlation not only predicts the

beginning of intermittent separation between Stations 11 and 13 but the reattachment location between Stations 26 and 28 also.

In the fully developed separation region Simpson et al. (ref. 1) demonstrated that a similarity existed in the forward flow fraction profiles by normalizing and plotting

$$\frac{\gamma_{P_U} - \gamma_{P_{U_{\min}}}}{1 - \gamma_{P_{U_{\min}}}} \text{ vs. } \frac{y}{M} \quad (5-32)$$

where $\gamma_{P_{U_{\min}}}$ was the minimum value of γ_{P_U} in the profile near the wall and M was the distance from the wall to the peak in the axial turbulence profile. The data in the present experiment were normalized in the same manner and very good profile similarity was obtained. However, better similarity was obtained when the profiles were normalized with M chosen as the distance from the wall to the peak in the transverse turbulence profile. The profiles normalized by the distance from the wall to the peak in the transverse turbulence profile are plotted in figure 5-17. Data scatter is very small, being well within the bounds of Simpson's data which are based on M chosen as the distance from the wall to the peak in the axial turbulence profile.

5.5 Description of the Separation Bubble

Downstream of separation a large separation bubble, defined as Zone III in figure 5-1, having a maximum thickness, h , of 17 cm was formed between the mean dividing streamline and the upper wall test surface. The flow within the bubble was characterized by vigorous recirculation and high turbulence levels. As shown in figure 5-18, Zone III can be partitioned into three transverse subzones: Zone IIIA, the backflow boundary layer in which $U < 0$ and $\partial U / \partial y < 0$; Zone IIIB, the backflow shear layer in which $U < 0$ and $\partial U / \partial y > 0$; and Zone IIIC, the forward flow shear layer, in which $U > 0$ and $\partial U / \partial y > 0$. The backflow in Zones IIIA and IIIB was strong and steady. Mean backflow velocities exceeding 30 percent of the local freestream velocity have been measured within these subzones. Steady backflow (i.e., $\gamma_{P_U} = 0$) was measured over a large portion of zones IIIA and IIIB. As indicated in figures 4-13, 5-13, and Table II, the region throughout which the forward flow fraction was zero extended along the test surface from Station 18 ($x = 67.3$ cm) to Station 24 ($x = 90.2$ cm). The maximum thickness of the steady backflow region was 2.5 cm at Station 20 ($x = 74.9$ cm). Measurements of $\gamma_{P_U} = 0$ in a separated boundary layer have not been reported previously (ref. 24).

As a result of the strong steady backflow within the separation bubble a well developed thin backflow boundary layer (Zone IIIA) grew along the test plate. The boundary layer, which had both laminar and turbulent characteristics, will be described in more detail in Section 5.5.1 below.

Zone IIIB, the backflow shear layer, was approximately an order of magnitude thicker than the backflow boundary layer. The backflow shear layer consisted of an inner layer having a relatively flat velocity profile (Zone IIIB1), which connected the viscous near wall region with the outer shear flow, and the outer backflow region (Zone IIIB2) which was part of the outer shear flow. Zones IIIA, IIIB1, and IIIB2 are components of the three-layer backflow model proposed by Simpson (ref. 1). Zone IIIB was characterized by a nearly constant turbulence level approximating 8 percent of the inlet free-stream velocity as shown in figure 4-18.

Zone IIIC, the forward flow shear layer, defined as the region between the locus of $U=0$ points and the dividing streamline ($\psi = 0$) contained higher normal velocity gradients, $\partial U/\partial y$, and turbulence levels than Zone IIIB. In fact, the largest values of $\partial U/\partial y$ within the reversed flow region between Stations 13 and 26 occurred at the outer edge of Zone IIIC. As discussed below in Section 5.8, "Shear Stress Correlations" the largest values of the streamwise shear stress, $\alpha\beta$, also occurred at the outer edge of Zone IIIC near the dividing streamline. As shown in figure 5-19, Zone IIIC was slightly thinner than the combined thicknesses of the backflow zones (Zone IIIA + Zone IIIB) at all stations. The thicknesses of the backflow zones and the forward flow shear layer (Zone IIIC) increased linearly over the upstream half of the separation bubble. The origin of the linear growth region was the point of transitory detachment (i.e., $\gamma_{p_U} = 0.50$ at the wall).

5.5.1 Description of the Backflow Boundary Layer

Although the existence of a steady backflow boundary layer was not anticipated at the outset of the test program, the measurement matrix was sufficiently dense to permit a limited analysis of the structure of the backflow boundary layer. Backflow velocity profiles are plotted in figure 5-20. The profiles were calculated from backward-facing pitot data. The limited number of LV measurements made within the backflow boundary layer indicated that the backflow was steady ($\gamma_{p_U} = 0$) between Stations 23 and 18 (i.e. over the central 35 percent of the axial extent of the bubble) and only slightly intermittent ($\gamma_{p_U} < 0.12$) at all other locations. LV velocity measurements were in good agreement with the pitot data.

The boundary layer appeared to originate near the reattachment point ($x_R = 103$ cm) just downstream of Station 27. The boundary layer grew until it reached a maximum thickness of approximately 0.76 cm at Station 15 near Zone II, the intermittent separation zone. The pitot data obtained at Station 15 are not presented in figure 5-20 because values of γ_{p_u} as high as 25 percent measured near the wall at Station 15 could make the data unreliable.

With the understanding that the accuracy would be less than desired because of the small number of data points obtained within the backflow boundary layer, boundary layer integral properties were calculated for each profile presented in figure 5-20. Calculated values of the momentum thickness Reynolds number, Re_θ , the shape factor, H , and other backflow boundary layer parameters are listed in Table VII. Boundary layer parameters determined by Coles (ref. 30) for a zero pressure gradient turbulent boundary layer are also listed in Table VII for comparison. Although the maximum calculated value of Re_θ , which was 184, was much lower than the value of 425 required for transition in low-freestream-turbulence, zero-pressure-gradient boundary layers (Table 2 in Appendix A of ref. 30), the calculated value of H was transitional. The shape factor decreased from 1.98 at Station 25 to 1.48 at Station 16. The values are between the shape factor of 2.59 for a laminar boundary layer having a Blasius velocity profile (ref. 35) and the value of 1.47 given by Coles (ref. 30) for a turbulent boundary layer for which Re_θ equals 855.

To gain additional insight into the nature of the backflow boundary layer the local axial turbulence levels, $\sqrt{u^2}/U$, measured within Zone IIIA with the LV system were plotted in figure 5-21. The turbulence level was uniformly high across the boundary layer, varying from approximately 50 percent near the wall to 40 percent at the "freestream." The turbulence was dominated by low frequency large scale eddies (see Section 4.6). The turbulence profile measured by Klebanoff (ref. 31) for a flat plate turbulent boundary layer having a low level of freestream turbulence has been shown for comparison. The local turbulence levels in the Klebanoff profile are less than 10 percent over the outer 90 percent of the boundary layer. Because of the low free-stream turbulence level, the Klebanoff boundary layer is dominated by turbulence which is generated near the wall and diffused outward. If such turbulent transport exists in the backflow boundary layer it is masked by the large scale turbulent eddies.

The turbulence levels within the backflow boundary layer exceed the turbulent boundary layer values measured by Klebanoff at all points in the profile. In this respect, the backflow boundary layer is clearly turbulent. However, it could be argued that the LV turbulence measurement resulted from averaging highly unsteady laminar flow at the wall which is driven by the

large scale turbulent eddies in the "freestream." Therefore, the backflow boundary layer can only be referred to as pseudo-turbulent until its exact nature can be determined from more detailed measurements.

Simpson (ref. 26) has proposed that the backflow velocity profile in Zones IIIA and IIIB has a universal shape defined by the equations

$$\frac{U}{|U_N|} = A \left(\frac{y}{N} - \ln \left| \frac{y}{N} \right| - 1 \right) - 1 \quad (5-33)$$

where N is the value of y at the transverse location of the maximum backflow velocity, U_N . The present LV data are compared to the Simpson correlation in figure 5-22. Setting $A = 0.3$ as suggested by Simpson, eq. (5-33) correlated only the profile data at Station 15 just downstream of detachment. Setting $A = 0.2$ provided a better correlation for data in Zone III A (i.e., $y/N < 1$). Considering the scatter in the profiles in Zone IIIB when plotted in y/N vs. U/U_N coordinates, eq. (5-33) could not correlate the Zone IIIB data for any value of A . Simpson also noted difficulties in using eq. (5-33) to correlate Zone IIIB profiles.

The flow at Station 15 most closely approximated the flow conditions used in the test cases surveyed by Simpson in developing eq. (5-33). The velocity at Station 15 was intermittent having a minimum value of γ_{p_U} of 0.08. All other profiles presented, except the Station 16 data, had steady backflow (i.e., $\gamma_{p_U} = 0$) throughout the profile. None of the profiles surveyed by Simpson had steady backflow at any point in the profile.

Because of the highly turbulent nature of the backflow boundary layer, an attempt was made to plot the backflow data in U^+ vs. y^+ law-of-the-wall coordinates. Simpson had suggested (ref. 1) that such a scaling was not possible in the backflow boundary layer because the law-of-the-wall length scale ν/U_τ varies inversely with its velocity scale U_τ which differs from the behavior of N and U_N which both increased in the downstream direction. In the present data, the behavior noted by Simpson occurred over a short region just downstream of detachment (Stations 13-15) where $\gamma_{p_U} > 0$ as shown in figure 5-14. In the steady backflow region (Stations 18-24), however, N increased in the direction of the backflow while U_N remained relatively constant (see Table VII) which is exactly the behavior attributed to boundary layers which can be modeled in law-of-the-wall coordinates.

Backflow boundary layer data plotted in law-of-the-wall coordinates are presented in figure 5-23. The data are characterized by a short log-linear region ($11 < y^+ < 60$) and a negative wake. Data scatter is minimal. The absence of a wake component in the backflow boundary layer is not surprising. Coles has plotted the strength of the wake component in equilibrium turbulent flow vs. Re_θ in figure 12 of reference 30. Coles's plot shows that the magnitude of the wake component is zero at $Re_\theta = 425$ and increases to its equilibrium value at $Re_\theta = 5000$. The maximum value of Re_θ in the backflow boundary layer was 184. Coles also noted in figure 15 of reference 30 that increasing freestream turbulence decreased the strength of the wake component. Kline et al. (ref. 52) showed that the wake component in an equilibrium turbulent boundary layer, which was normal at a freestream turbulence level of 1.8 percent, decreased to zero when the freestream turbulence level increased to 4.5 percent. As shown above in figure 5-21 the backflow boundary layer had a "freestream" turbulence level of 40 percent.

The friction velocity, U_τ , and the skin friction coefficient, $C_f = -2 (U_\tau/U_{ref})^2$, were determined from the law-of-the-wall plots. The skin friction values, shown in figure 5-23, were approximately an order of magnitude lower than the values measured in the attached boundary layer upstream of separation. However, when localized by the local maximum backflow velocity, U_N , rather than the inlet reference velocity, the skin friction coefficient, $C_f' = 2 (U_\tau/U_N)^2$, was quite large. C_f' has been plotted vs. $Re_{x'}$, in figure 5-24 where $Re_{x'} = U_N x' / \nu$ and $x' = x_R - x$ where x_R , the axial location of reattachment, equaled 103 cm.

Also plotted in figure 5-24 are values of C_f' estimated from the normal velocity gradient at the wall at each station within Zone III using the following equation

$$C_f' = \frac{\mu \left. \frac{\partial U}{\partial y} \right|_{y=0}}{\rho U_N^2 / 2} + \frac{Re_\theta}{2} \frac{\Delta y}{\theta} \frac{\partial U_N}{\partial x} \quad (5-34)$$

The second term on the rhs of eq. (5-34) is a correction term to be used in flows having axial pressure gradients (ref. 53). The correction term did not exceed 12.5 percent at any station within Zone III.

C_f' calculated from eq. (5-34) decreased from 0.022 at $Re_{x'} = 2.1 \times 10^4$ near reattachment to 0.0074 at $Re_{x'} = 1.1 \times 10^5$ near detachment. Very good agreement was obtained between values of C_f' calculated using eq. (5-34) and the values determined from the law of the wall plots. Values of C_f' correlated reasonably well with the equation

$$C_f' = 3.29 \operatorname{Re}_x^{-1/2} \quad (5-35)$$

which has the same $\operatorname{Re}_x^{-1/2}$ dependence but which is 400 percent higher than zero pressure gradient laminar skin friction coefficients at the same Reynolds number.

Two possible explanations for the high skin friction coefficients measured in the backflow boundary layer could be the favorable pressure gradient and the high turbulence levels impressed upon the backflow boundary layer by the external flow field. The effect of the favorable pressure gradient on the shear at the wall can be estimated using the Pohlhausen parameter, Λ , (ref. 35, p. 245)

$$\tau_w = \mu \left. \frac{\partial U}{\partial y} \right|_{y=0} = \mu \frac{U_N}{N} \left(2 + \frac{\Lambda}{6} \right) \quad (5-36)$$

where

$$\Lambda = - \frac{dp}{dx'} \frac{N^2}{\mu U_N}$$

The effect of the pressure gradient on the skin friction can be estimated from eq. (5-36) as

$$\frac{C_{f\Lambda}'}{C_{f\Lambda}'(\Lambda=0)} = 1 + \frac{\Lambda}{12} \quad (5-37)$$

The maximum value of Λ within the backflow boundary layer occurred at Station 23 ($x = 86.4$ cm) where $\Lambda = 13.9$. Thus, the effect of the favorable pressure gradient could account for as much as 100 percent of the 400 percent increase in skin friction at some points in the backflow boundary layer.

The effect of freestream turbulence in reducing the transition Reynolds number and increasing the skin friction coefficient is well known but not well quantified. Dyban et. al. (ref. 54) have measured a 56 percent increase in skin friction in a laminar boundary layer having a 25 percent freestream turbulence. The increase in the backflow boundary layer skin friction coefficients due to the 40 percent "freestream" turbulence within the

separation bubble would be expected to be large but cannot be estimated at this time.

5.6 Description of the Reattachment Process

Reattachment of the separated shear layer is an inherently unsteady process which occurs within Zone IV, the Reattachment Zone. Smoke flow visualization movies showed that the Reattachment Zone was characterized by random streamline flapping (shown schematically in figure 4-6) with large scale eddies being convected alternately upstream and downstream from the impingement point on the test surface. The reattaching flow, impinging steeply onto the test surface, caused a static pressure peak which drove the strong backflow within the separation bubble described above.

The flow within Zone IV was characterized by frequent flow reversals and high turbulence levels. The flow reversals have been quantified by the forward flow fraction, which is the fraction of the time the flow is moving in the downstream direction. Values of the forward flow fraction, γ_{PU} , near the test surface ($y = 0.10$ cm) at the four LV measurement stations within the reattachment zone have been plotted in figure 5-25 versus x^* , a non-dimensional axial coordinate

$$x^* = \frac{x - x_R}{x - x_{\delta^*_{\max}}} \quad (5-38)$$

where x_R is the reattachment location defined as the point on the test surface where $\bar{C}_f = 0$ and $x_{\delta^*_{\max}}$ is the axial coordinate at the location of the maximum separation bubble thickness. The definition of the non-dimensional coordinate, x^* , has been chosen to permit direct comparison of data in the reattachment zone to data obtained in backward facing step flows where the x -coordinate has its origin at the step and $x^* = (x - x_R)/x_R$ (ref. 17). Note in figure 5-25 that γ_{PU} rises from 0.02 at $x^* = -0.44$ to 1.0 at $x^* = +0.40$. If the reattachment zone is defined as the region between $0.01 \leq \gamma_{PU} \leq 0.99$ and $x - x_{\delta^*_{\max}}$ is approximately 1/2 the bubble length, the reattachment zone can be calculated to be 40 percent as long as the separation bubble. A correlation developed by Westphal et al. (ref. 17) for reattaching flow downstream of a backward facing step shows excellent agreement with the forward-flow fraction data obtained in the present study.

The skin friction coefficient measured within the reattachment zone has been plotted vs. the forward flow fraction in figure 5-26. The skin friction increased monotonically with forward flow fraction throughout the reattachment zone. Also plotted in figure 5-26 are data from two cases investigated by Westphal et al. (ref. 17) for reattaching flow behind a backward facing step. The backward facing step data showed similar trends to the data in the present study. In particular, for both cases studied by Westphal et al. and for the present data the location of $C_f = 0$ occurred near the location at which $\gamma_{PU} = 0.50$.

Downstream of the reattachment location the reattached flow recovers the structure of a flat-plate turbulent boundary layer. This process occurs in two stages. In Zone V, a new boundary layer develops along the test surface and quickly achieves equilibrium conditions. The relaxation of the outer shear layer in Zone VI occurs much more slowly, however.

Streamwise velocity and turbulence profiles downstream of reattachment are plotted in figure 5-27. The two-layer structure of the reattached boundary layer can be seen quite clearly in the figure as the new boundary layer grows rapidly toward equilibrium under the relaxing outer shear layer. The effective "freestream" turbulence level impressed upon the developing boundary layer was quite high. The turbulence level was approximately 10-14 percent of U_{ref} and on the order of 25 percent of the streamwise velocity at the edge of the new boundary layer at all measurement stations downstream of reattachment. Recovery of the two-layer profile to a flat-plate turbulent boundary layer profile was not complete at $x = 148$ cm, the final measurement station within the test section.

To study the structure of the recovering flat-plate turbulent boundary layer in more detail, axial velocity profiles at these measurement stations downstream of reattachment have been plotted in law-of-the wall coordinates in figure 5-28. At Station 28 ($x^* = 0.09$) at reattachment the boundary layer structure had no log-linear region. The profile was dominated by the wake-like structure of the reattaching outer shear layer. At Station 30 ($x^* = 0.36$) a short log-linear region had become established at $y^+ < 100$ but the profile dipped below the standard log-linear line before reverting to a strong, albeit somewhat diminished from Station 28, wake component at the edge of the boundary layer. At Station 34 ($x^* = 1.36$) the dip below the log-linear line persisted and the wake component had diminished to the extent that the profile had a negative wake component.

The dashed lines in figure 5-28 represent data obtained by Chandrsuda and Bradshaw (ref. 18) in a reattached fully developed turbulent mixing layer downstream of a backward facing step. The profiles obtained by Chandrsuda and

Bradshaw show the same characteristics as the profiles obtained in the present study. Chandrsuda and Bradshaw explained that the dip below the log-linear line occurred because the standard logarithmic law is based upon the assumption that the length scale of the turbulence is proportional to y , while at, and just downstream of, reattachment the length scale will be nearly constant, as it was in the separated shear layer, except very near the surface. Bradshaw and Wong (ref. 11) have shown that the dip persists for 50 step heights ($x^* = 7.5$) downstream before equilibrium is reached in the turbulence energy exchange between the small length scale turbulence being generated near the wall and the large length scale turbulence being fed into the developing boundary layer from the reattached mixing layer. In the present study $x^* = 7.5$ would correspond to an axial location approximately 160 cm (i.e., 3.75 bubble lengths) downstream of reattachment.

The displacement thickness, δ^* , the momentum thickness, θ , and the shape factor, H , have been calculated throughout the reattachment region and are plotted in figure 5-29. The open circles represent data calculated using eqs. (5-4) and (5-5) based on classical boundary layer theory and the solid circles represent pressure-based integral properties calculated using eqs. (5-8) and (5-10) (see Section 5.3.3 "Boundary Layer Integral Properties"). Also plotted in figure 5-29 are integral property data obtained by Driver and Seegmiller (ref. 14) in flow reattaching behind a backward facing step within an adverse pressure gradient. The displacement and momentum thicknesses have been non-dimensionalized by h which equaled the maximum separation bubble thickness of 17 cm in the present study and the step height in the Driver and Seegmiller study.

The data obtained by Driver and Seegmiller for their reference case in a nondiverging tunnel having zero pressure gradient in the reattachment zone are plotted as squares in figure 5-29. The trends shown in their data, namely the monotonic decrease in displacement and shape factor, and the generally increasing value of momentum thickness with axial distance are similar to the trends observed by Kim et al. (ref. 13) and Pronchick and Kline (ref. 16) for zero pressure gradient backward facing step flows. For flows reattaching in an adverse pressure gradient ($\alpha = 6$ deg) Driver and Seegmiller have shown that the displacement thickness decreases less rapidly and the momentum thickness increases more rapidly with axial distance than the zero pressure gradient case while the behavior of the shape factor is relatively unaffected by the pressure gradient. Conversely, in the present study the separated shear layer reattached within a converging channel ($\alpha = -38$ deg) having a very favorable pressure gradient downstream of reattachment. Thus, the rapidly decreasing displacement and momentum thicknesses downstream of reattachment in the present study follow the trends identified by the Driver and Seegmiller study of backward facing step flows. The behavior of the shape factor calculated from classical boundary layer theory was uninfluenced by the pressure

gradient (ref. 14 data), whereas the more accurate pressure-based shape factor calculated in the present study displayed a more rapid decrease with axial distance within the favorable pressure gradient.

5.7 Streamwise Turbulent Shear Stress Measurements

As noted by Cutler and Johnston (ref. 6), when the mean streamlines are inclined at a significant angle to the test surface, turbulent shear stress data are more meaningful when presented in an orthogonal coordinate system comprised of the mean streamline direction and the normal to the streamline than in a coordinate system orthogonal to the test surface. This is because flow history effects are important in boundary-layer flows (except near the wall) and the streamline orthogonal coordinate system can track the flow development along a given streamline. Cutler and Johnston concluded that the behavior of a turbulence quantity is more likely to be modeled in "universal" form if streamline orthogonal coordinates are used. In the current study, flow within the boundary layer was inclined more than 30 degrees relative to the test surface near separation and reattachment, significantly more than the 10 degree inclinations reported by Cutler and Johnston.

The Reynolds stress, \overline{uv} , data in the wall orthogonal (x,y) coordinate system can be rotated into the streamwise orthogonal (s,n) coordinate system using the following relation (ref. 6)

$$\overline{\alpha\beta} = \overline{uv} (\cos^2\phi - \sin^2\phi) + (\overline{v^2} - \overline{u^2}) \sin\phi \cos\phi \quad (5-39)$$

where $\overline{\alpha\beta}$ is the streamwise turbulent shear stress and $\phi = \tan^{-1} (V/U)$, the angle of the local mean-flow streamline to the wall. The wall orthogonal shear stress data presented in figure 4-21 have been rotated into streamwise orthogonal coordinates. The resulting values of $\overline{\alpha\beta}$ are tabulated in Table III and are plotted in figure 5-30.

Trends are much more evident in the streamwise shear stress profiles than in the \overline{uv} profiles plotted in figure 4-21. At Station 6 upstream of incipient detachment the shear stress peaks near the wall. At Station 11 as the boundary layer approaches detachment the peak increases in amplitude and moves away from the wall. Downstream of detachment, between Stations 13 and 18, the peak grows much more rapidly and is located near the edge of the backflow region (i.e., locus of $U = 0$ points) indicating strong turbulence generation in this region. Between Stations 22 and 28 aft of the maximum bubble thickness the peaks broaden and decay and move farther away from the $U = 0$ line into the

wake of the bubble. This decaying trend is reversed as the shear stress begins to grow again as the flow is accelerated into the exit duct at Stations 30 and 31. No data has been presented near reattachment where highly unsteady flow and steep flow angles make the rotated data of questionable value.

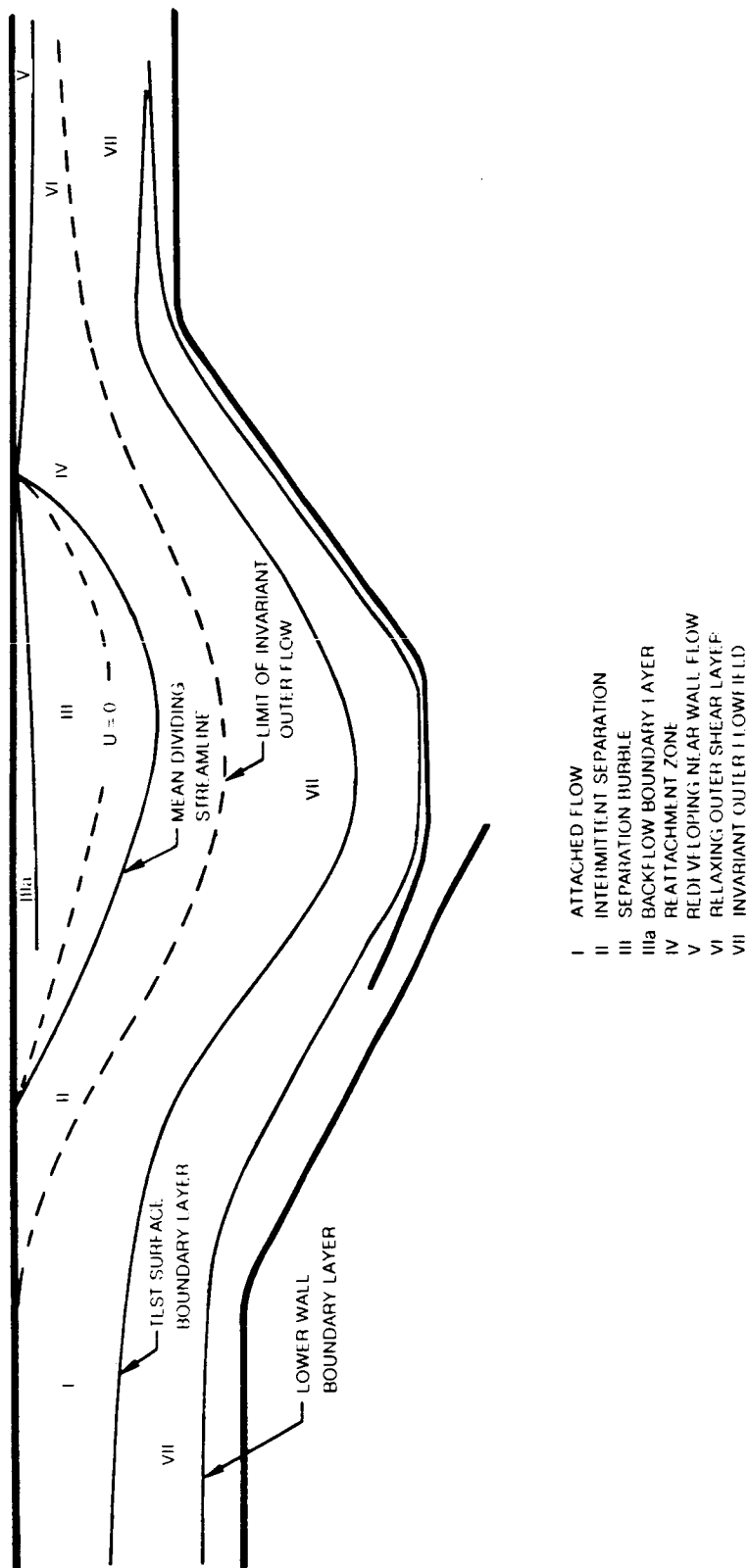


Figure 5-1 Separation Bubble Flow Zones

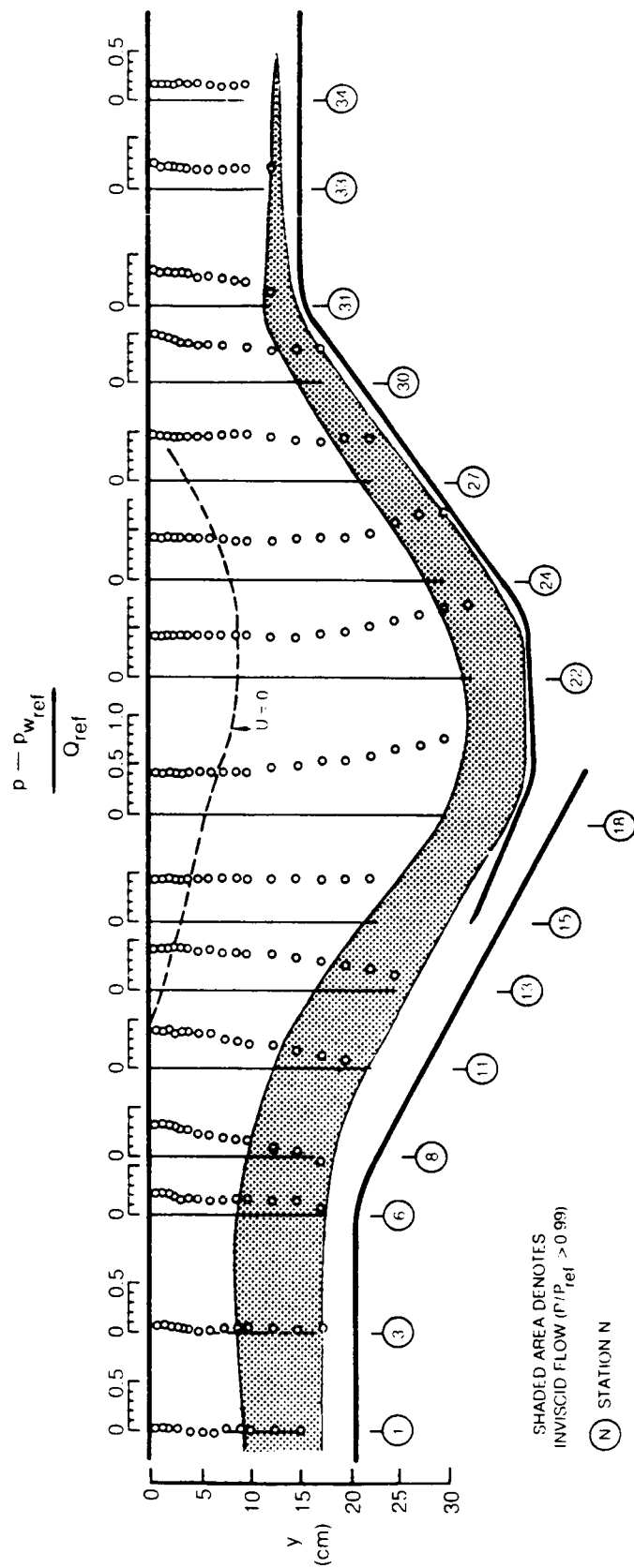


Figure 5-2 Static Pressure Profiles Calculated from Total Pressure and Laser Velocimeter Mean Velocity Measurements ($z = 0$)

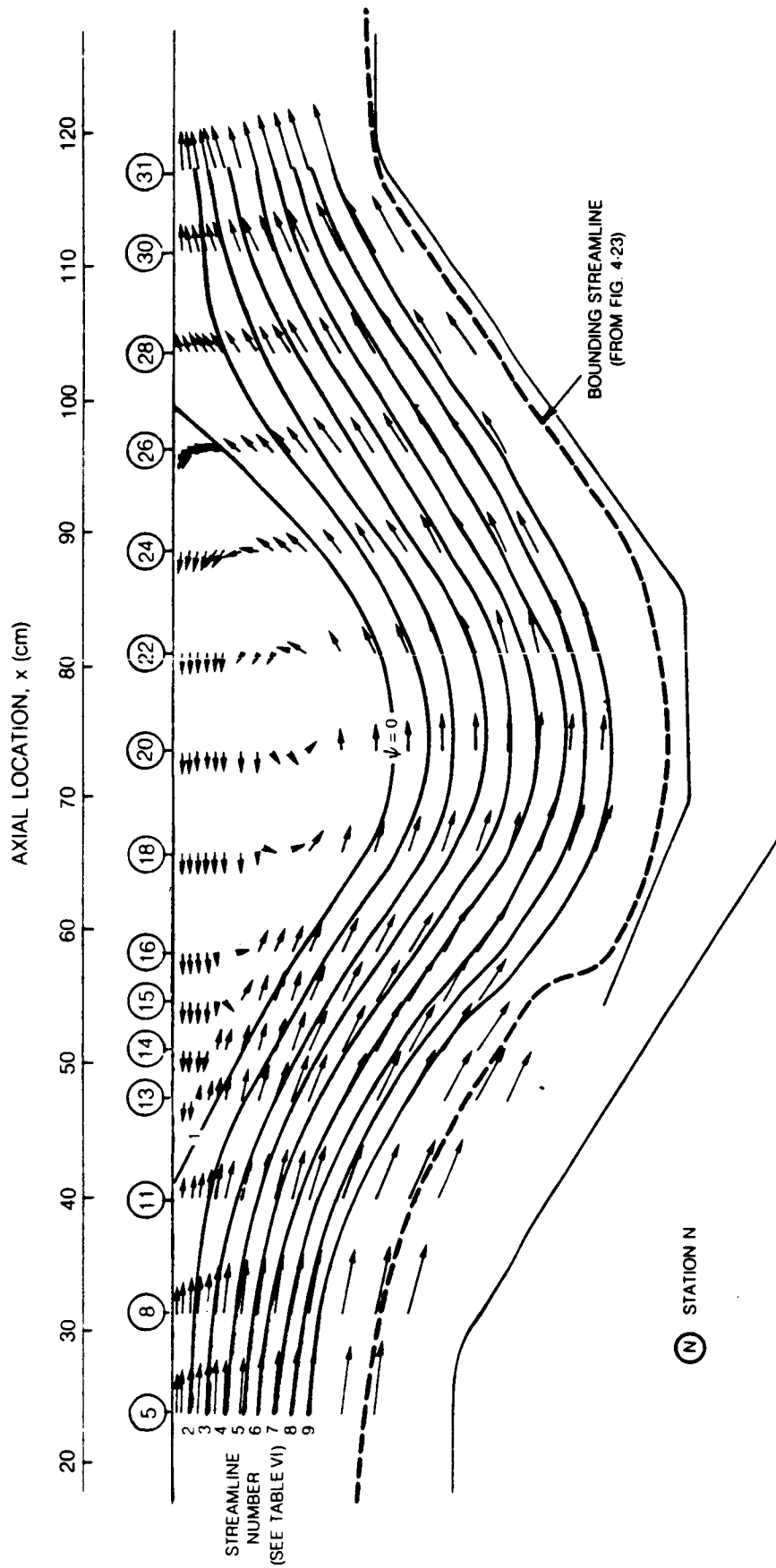


Figure 5-3 Velocity Vectors and Streamlines Determined from LV Mean Velocity Measurements on Wind Tunnel Centerline

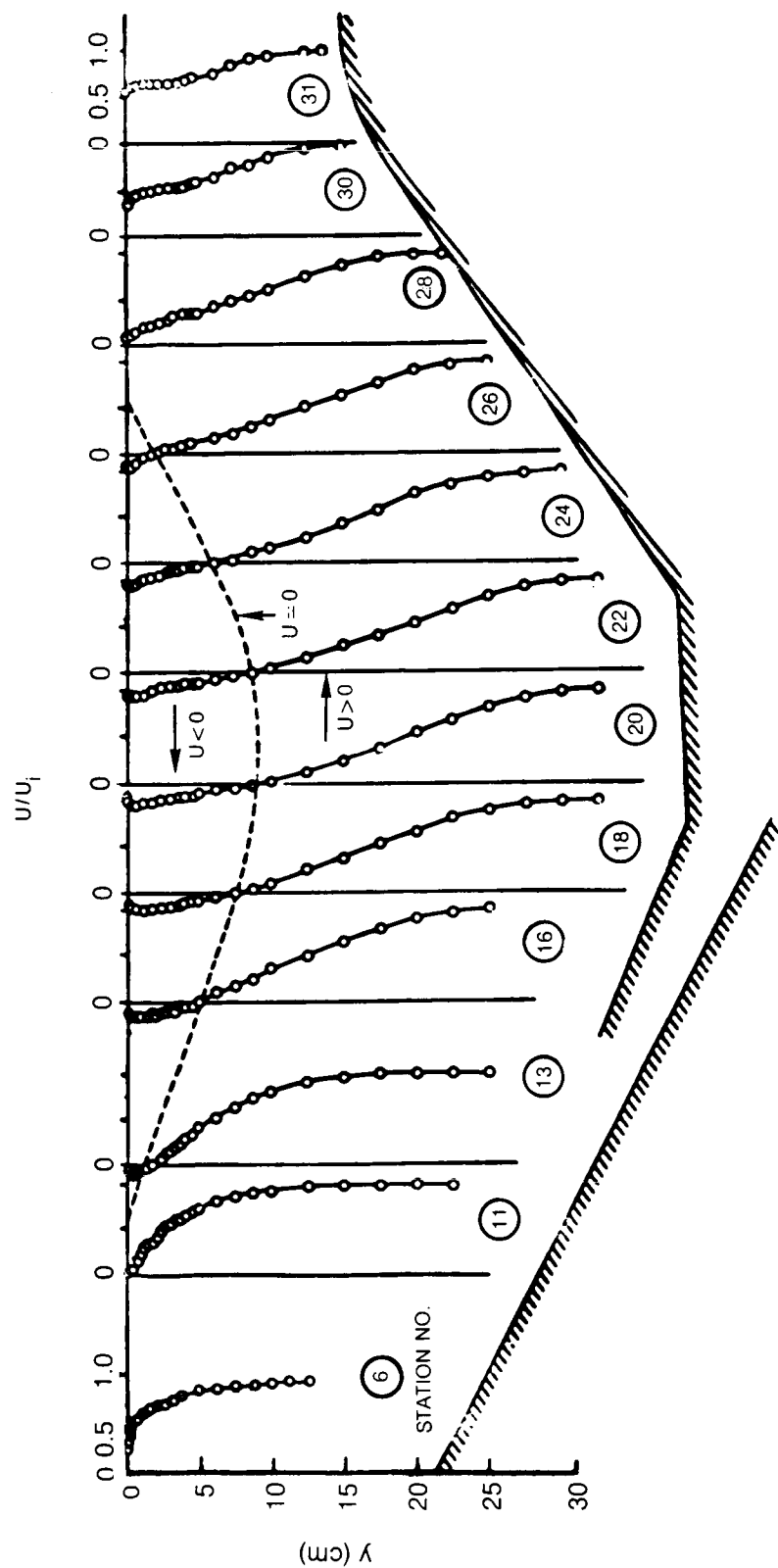


Figure 5-4 Normalized LDV Axial Velocity Measurements on Wind Tunnel Centerline

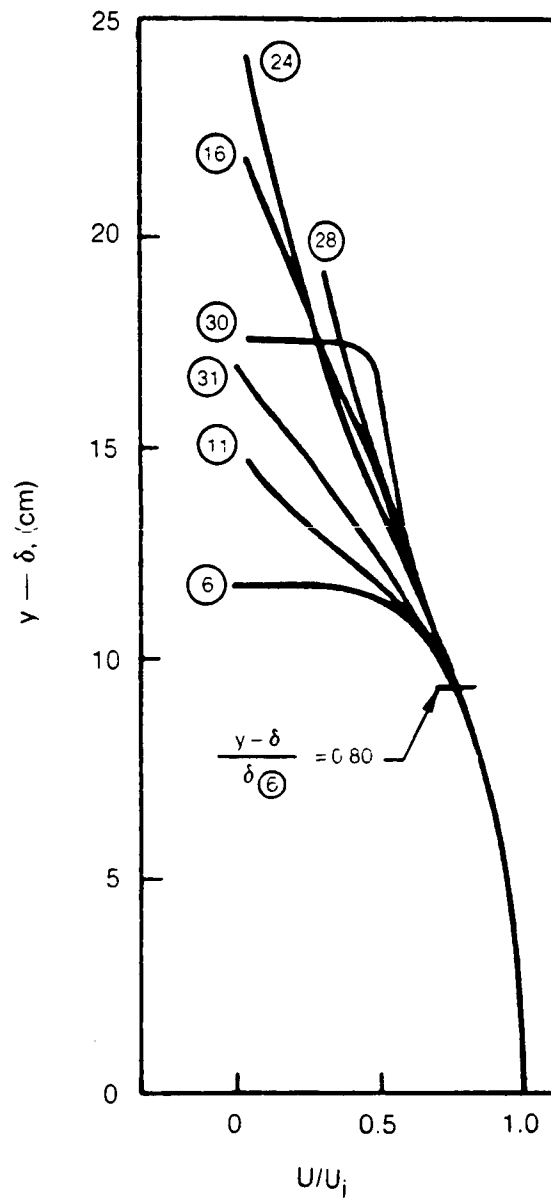


Figure 5-5 Normalized Axial Velocity Profiles Overlayed to Demonstrate Invariant Outer Boundary Layer Profile

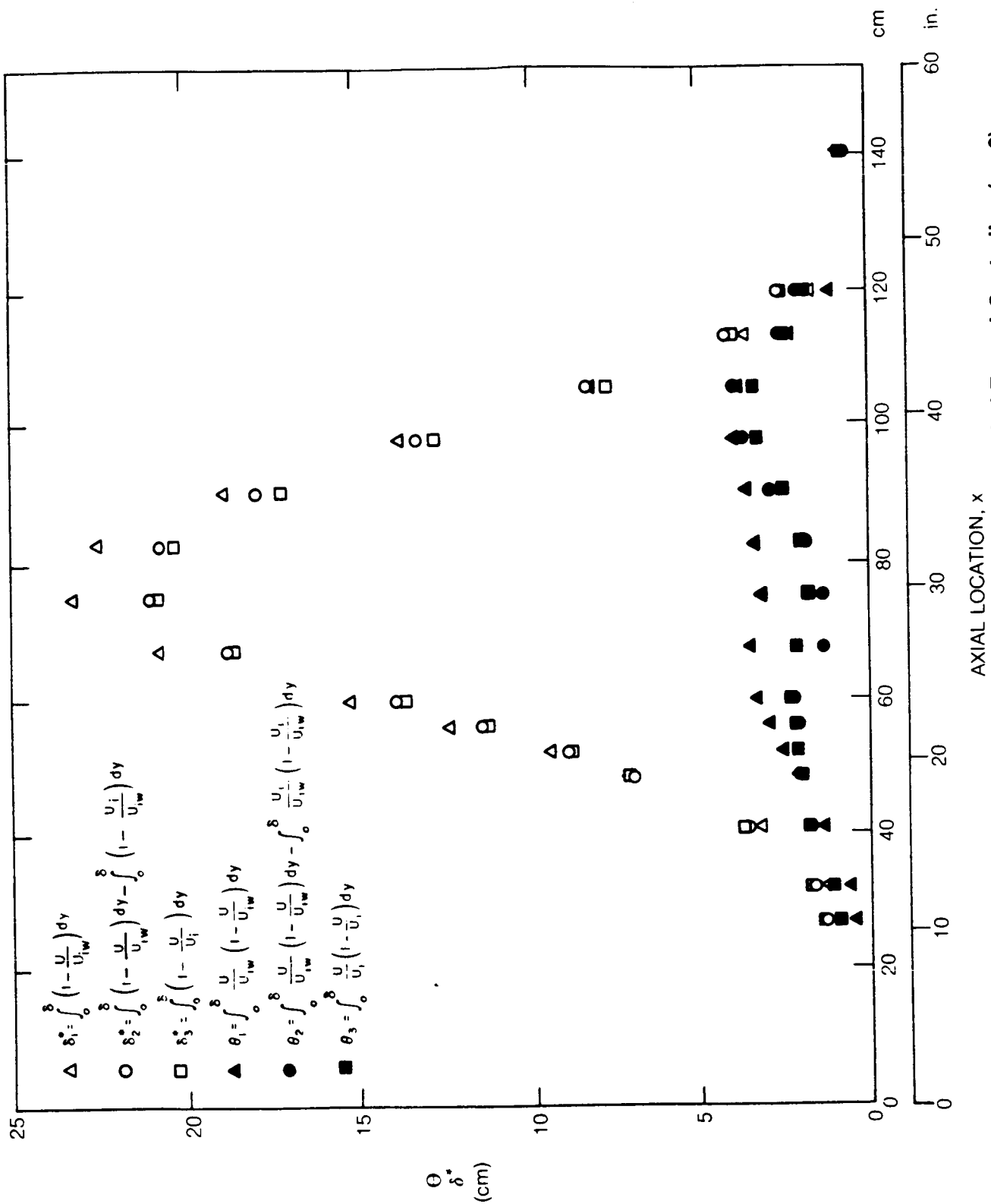


Figure 5-6a Displacement and Momentum Thickness on Wind Tunnel Centerline ($z=0$)

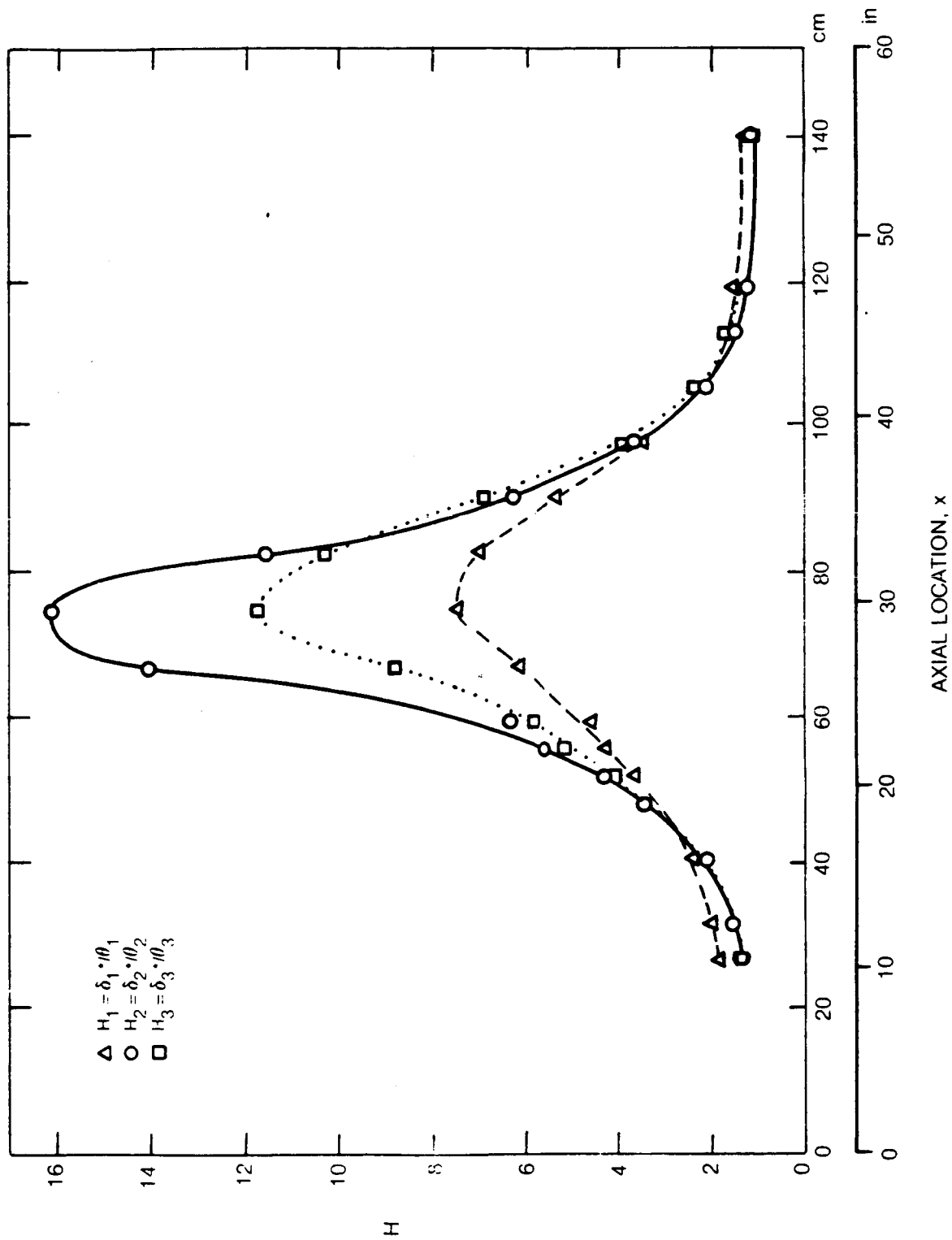
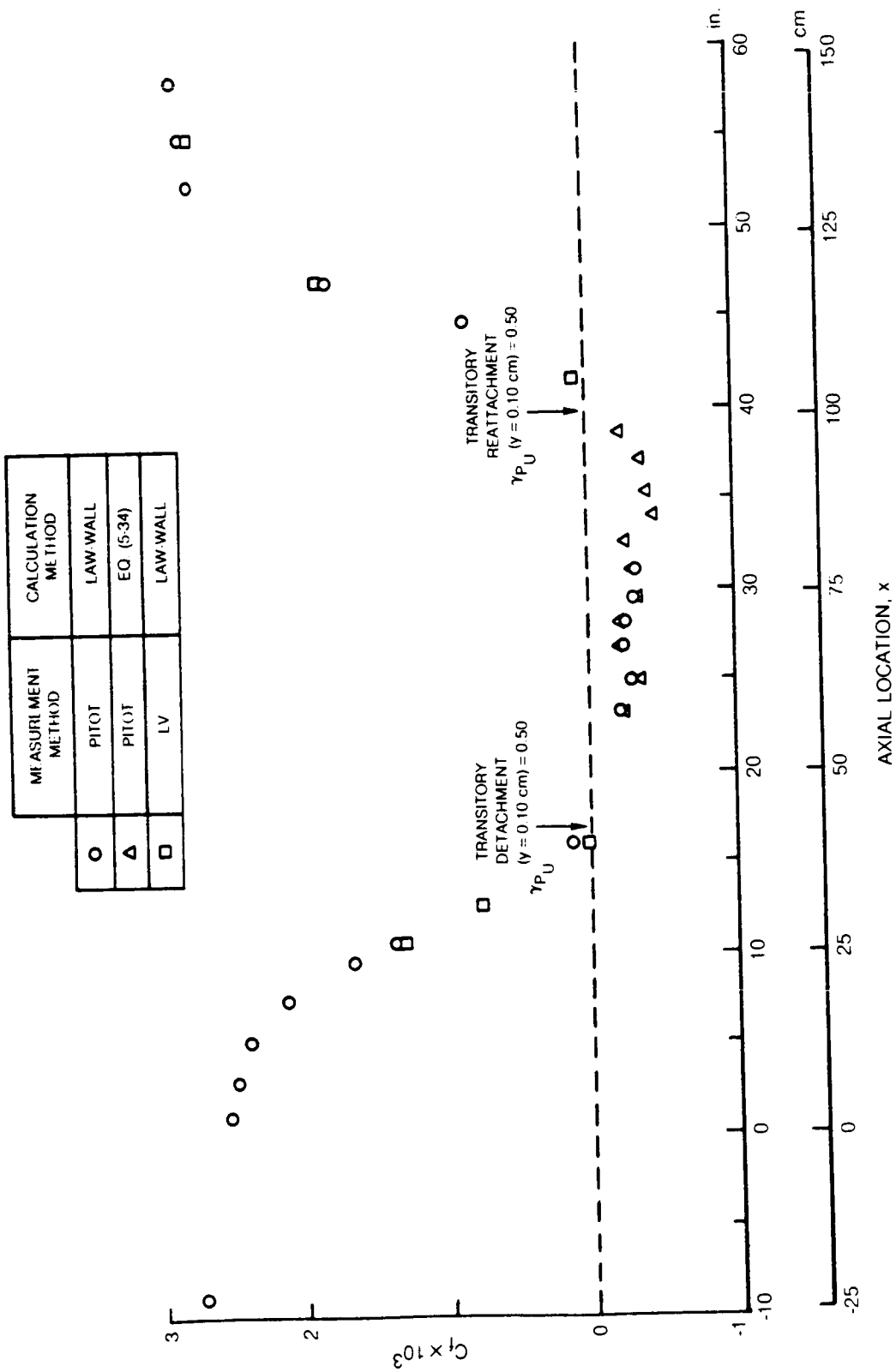
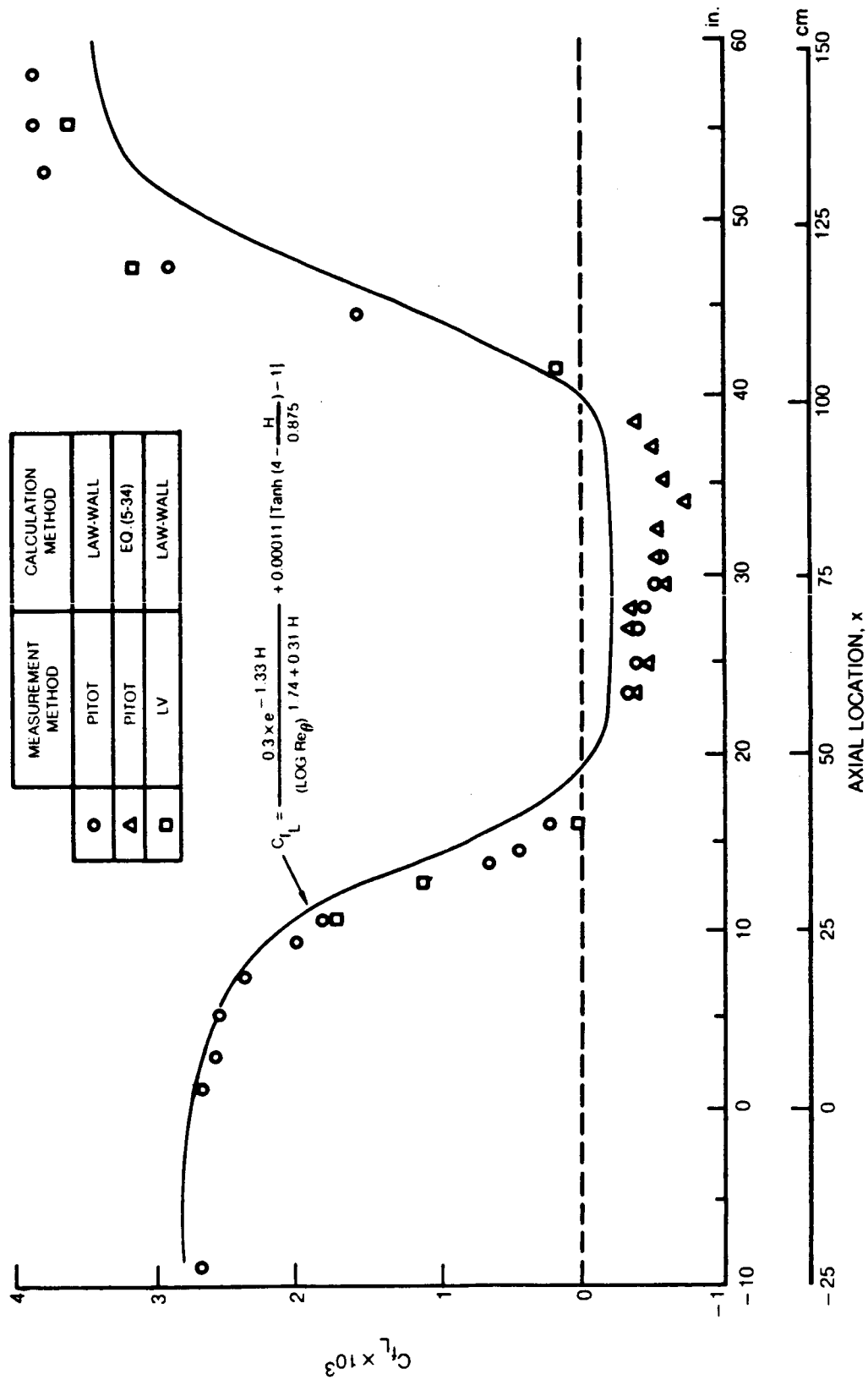


Figure 5-6b Shape Factor Determined from Laser Velocimeter Mean Velocity Measurements ($z = 0$)

Figure 5-7a Skin Friction Coefficient on Test Surface ($z = 0$)

Figure 5-7b Local Skin Friction Coefficient on Test Surface ($z = 0$)

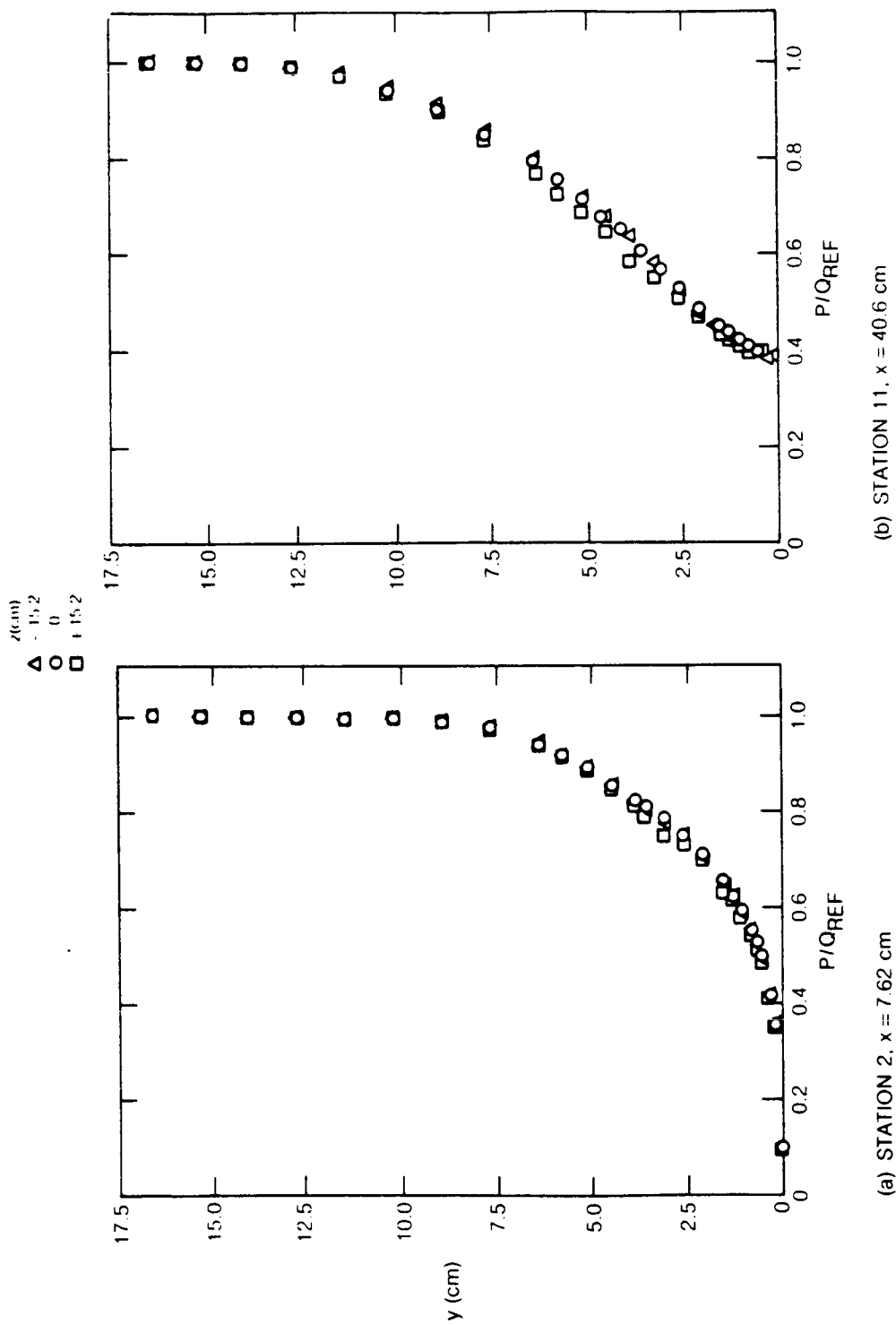


Figure 5-8 Total Pressure Profiles Showing Spanwise Uniformity of Flow

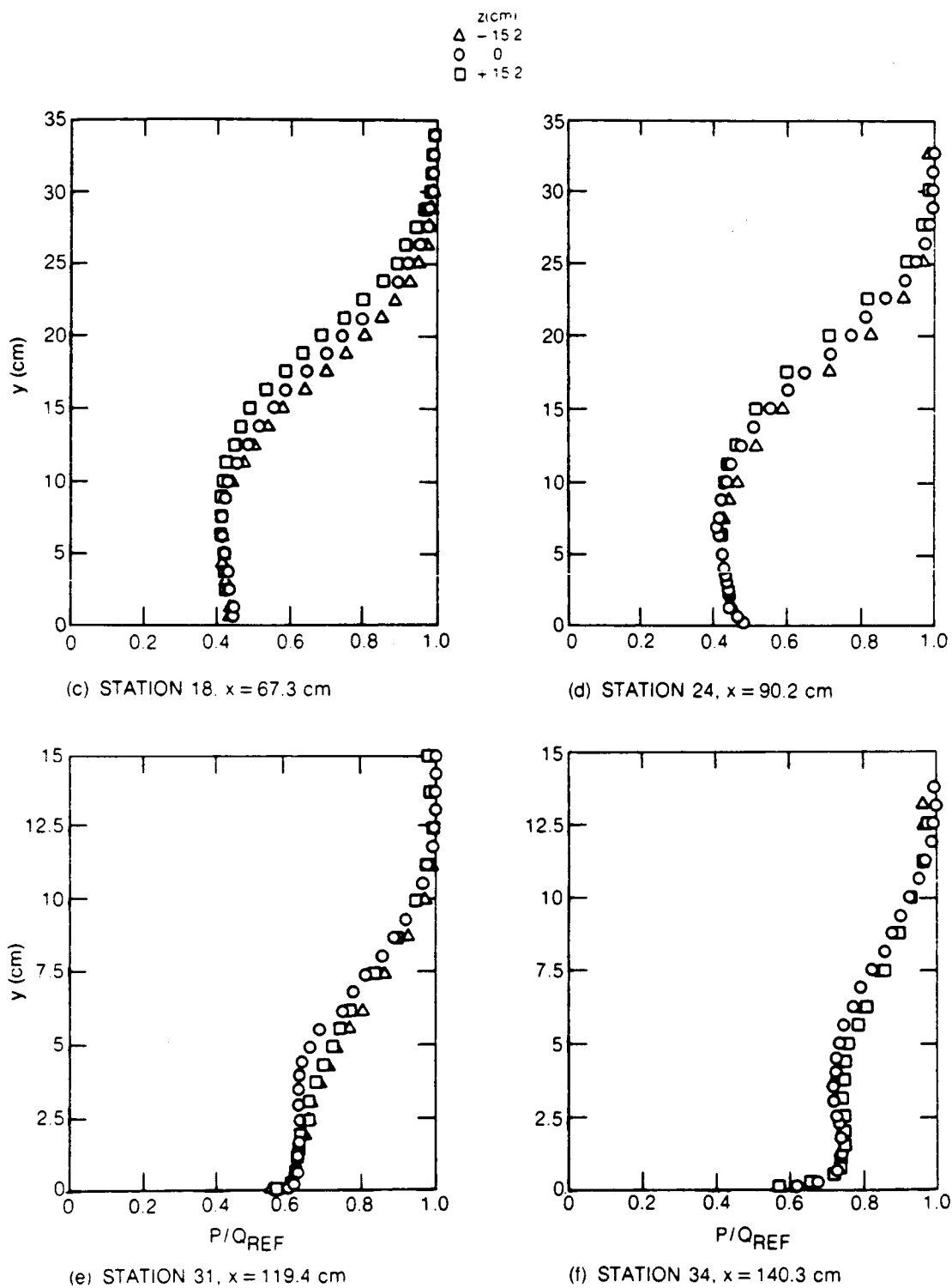


Figure 5-8 Total Pressure Profiles Showing Spanwise Uniformity of Flow (Concluded).

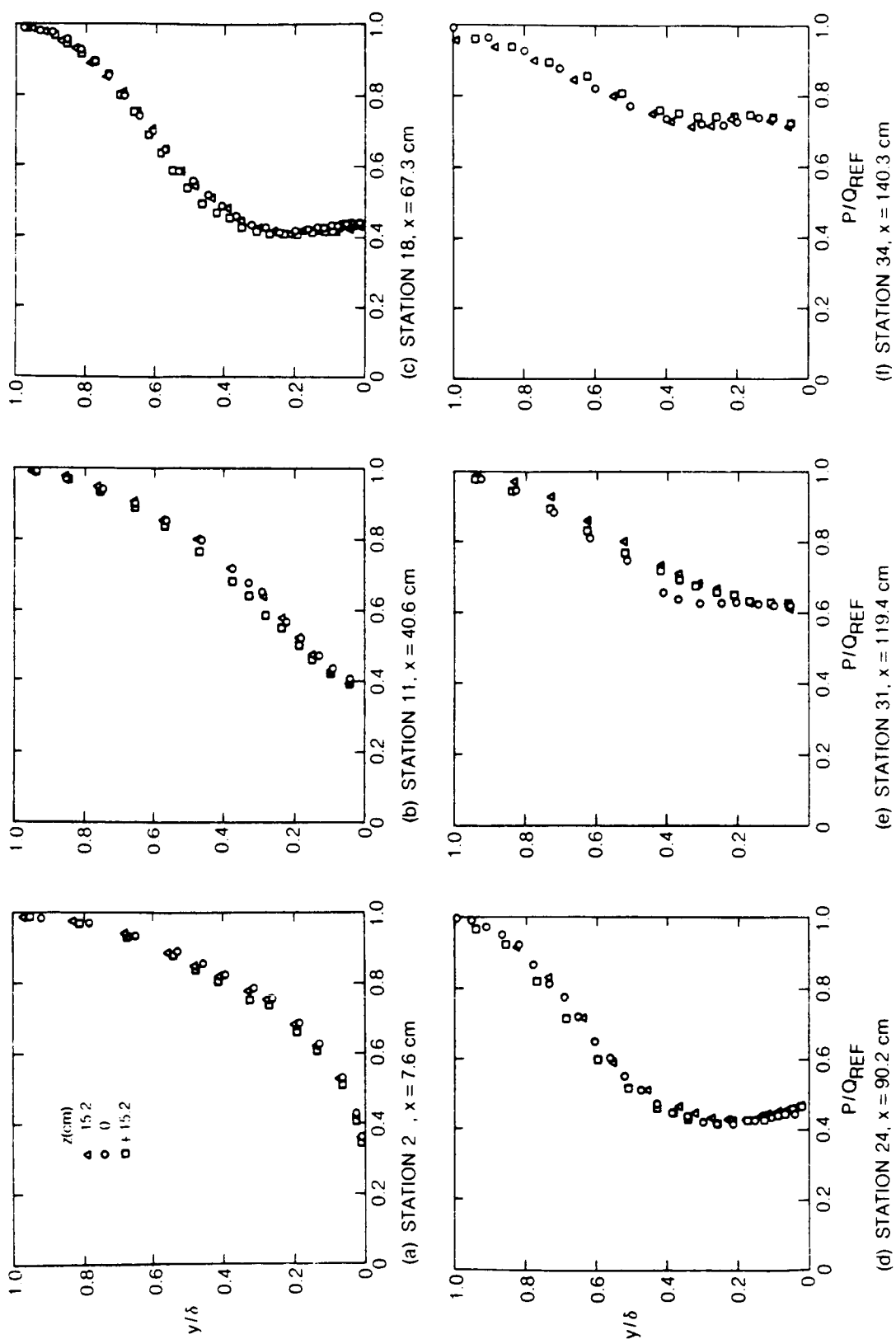
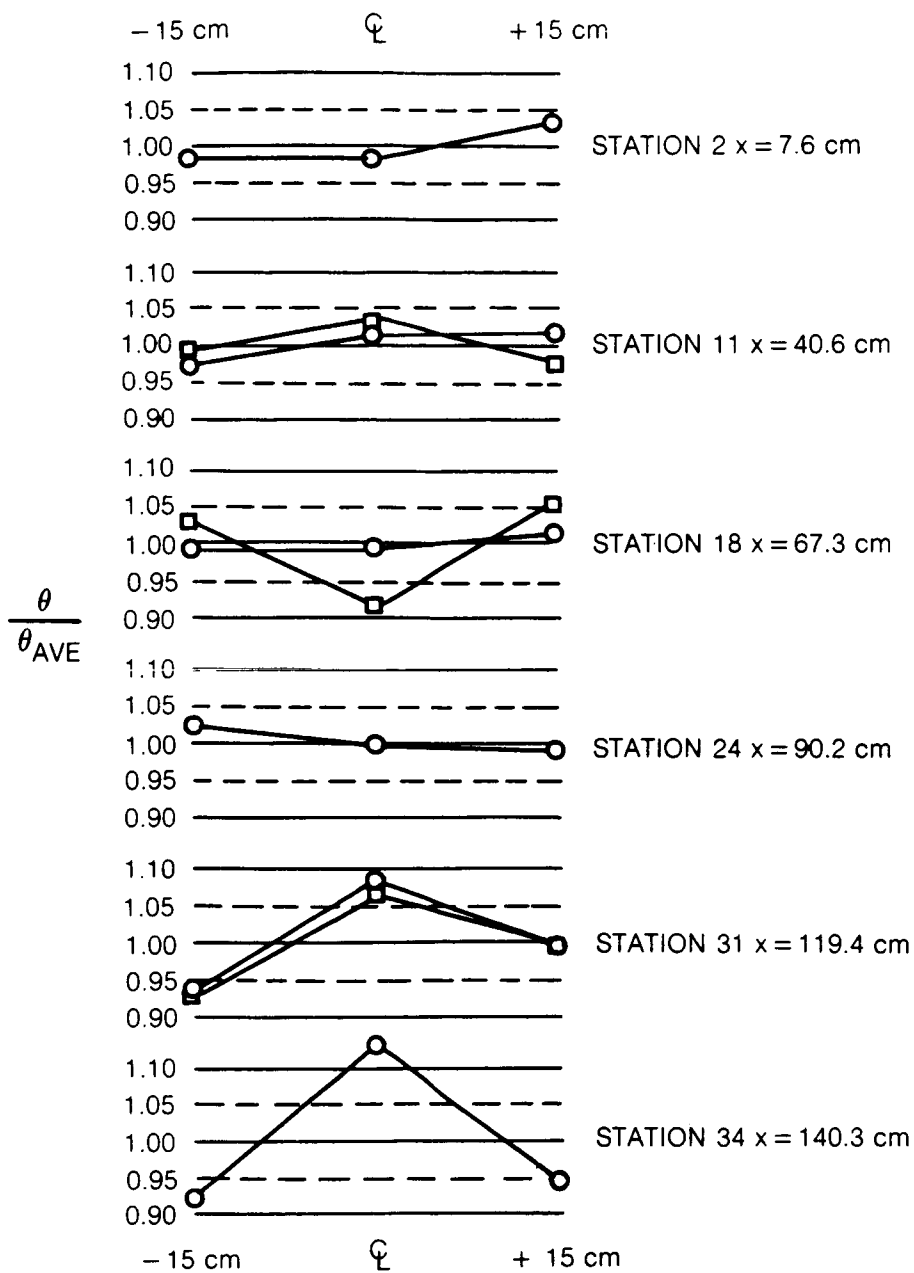


Figure 5-9 Normalized Total Pressure Profiles Showing Spanwise Uniformity of Flow



SPANWISE POSITION RELATIVE
TO TEST PLATE CENTERLINE

$$\begin{aligned} \bigcirc \theta_1 &= \int_0^{\delta} \frac{U}{U_{iw}} \left(1 - \frac{U}{U_{iw}} \right) dy \\ \bigcirc \theta_3 &= \int_0^{\delta} \frac{U}{U_i} \left(1 - \frac{U}{U_i} \right) dy \end{aligned}$$

Figure 5-10 Spanwise Variation in Momentum Thickness

	STATION NO	x	C _t	Π
		(cm)		
○	0	-24.13	0.00267	0.33
□	1	2.54	0.00252	0.42
△	2	7.62	0.00247	0.37
◇	3	13.34	0.00239	0.37
▽	4	19.05	0.00212	0.62
⊙	5	24.13	0.00165	1.26

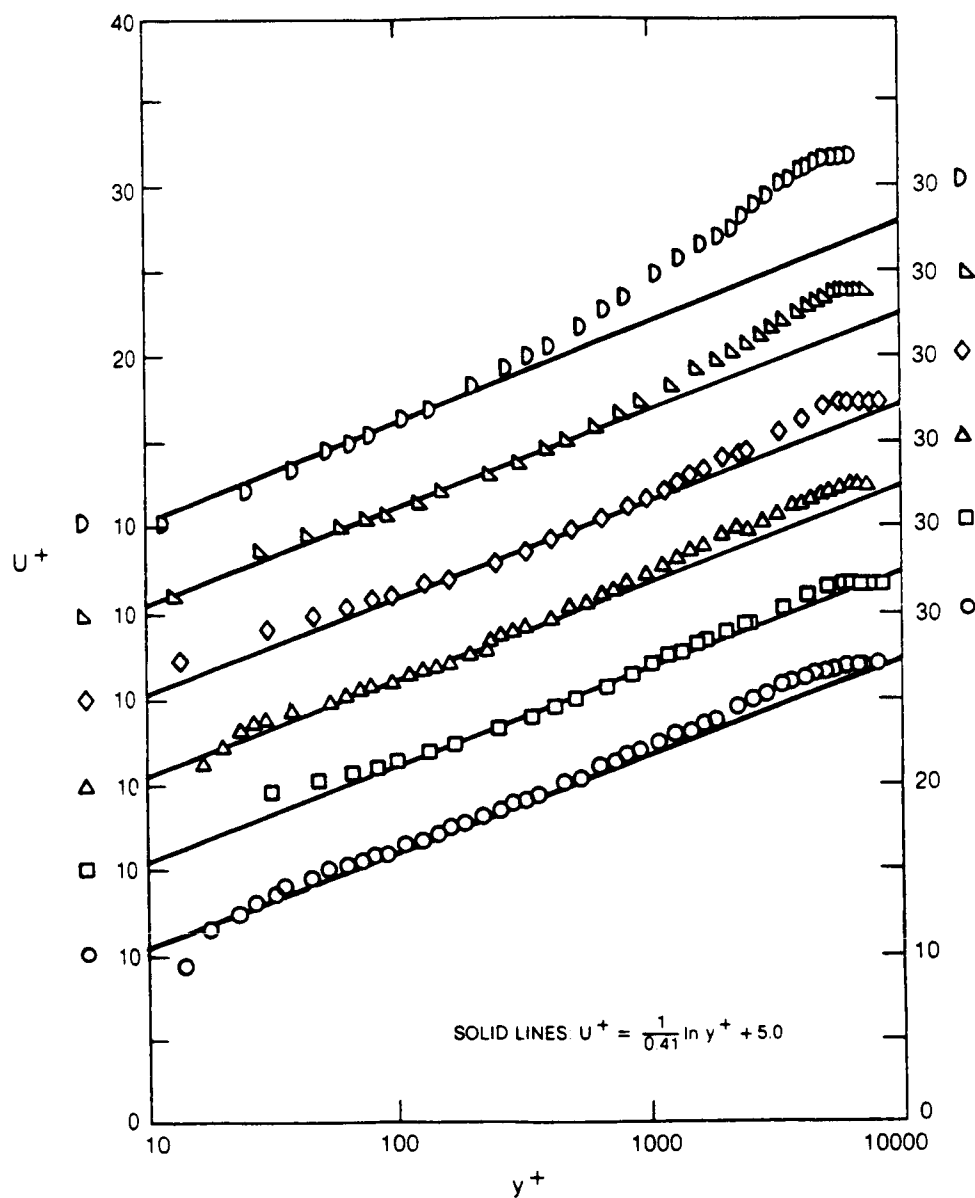


Figure 5-11a Law-of-the-Wall Velocity Profiles Upstream of Separation

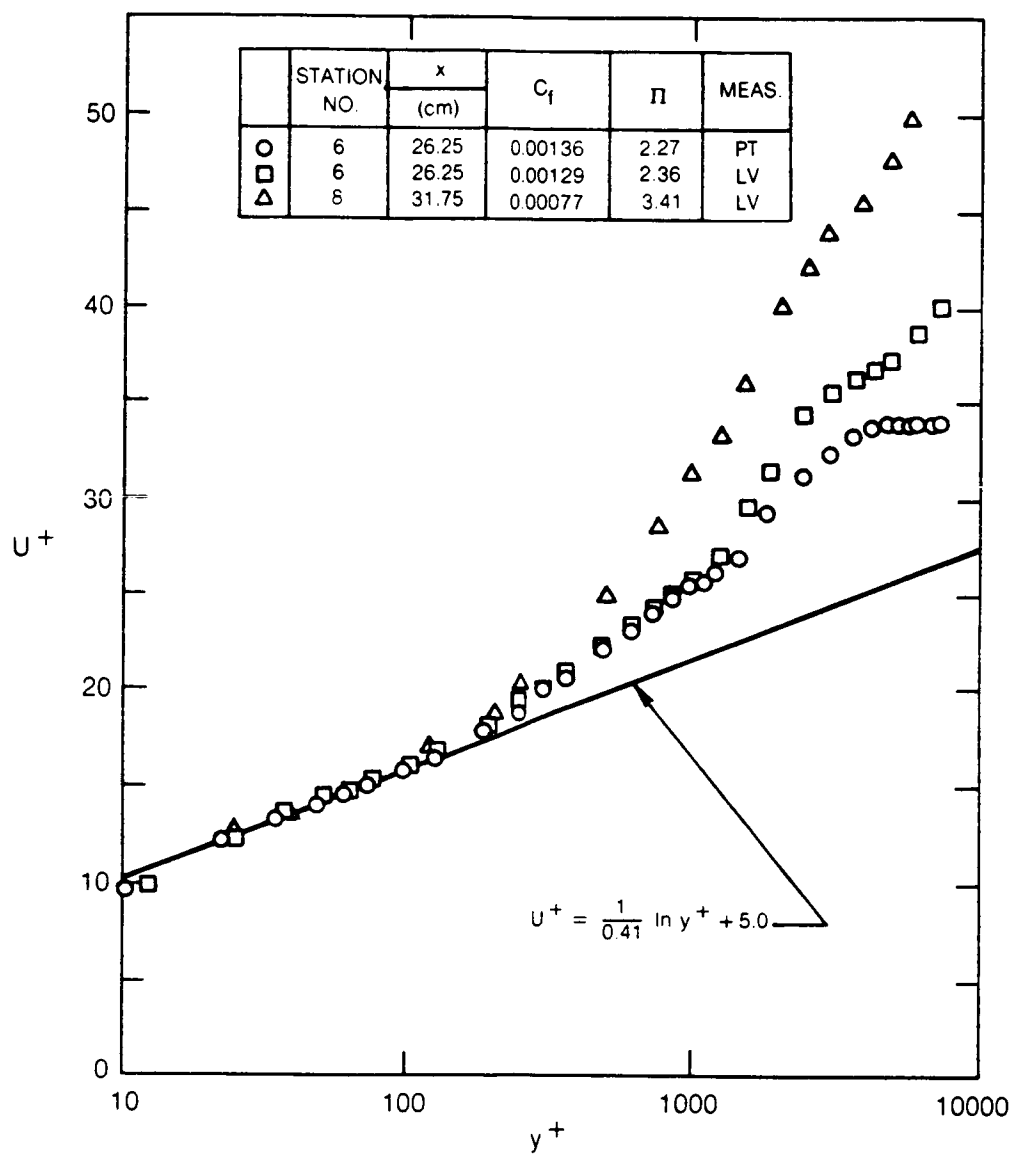


Figure 5-11b Law-of-the-Wall Velocity Profiles Upstream of Separation (Concluded)

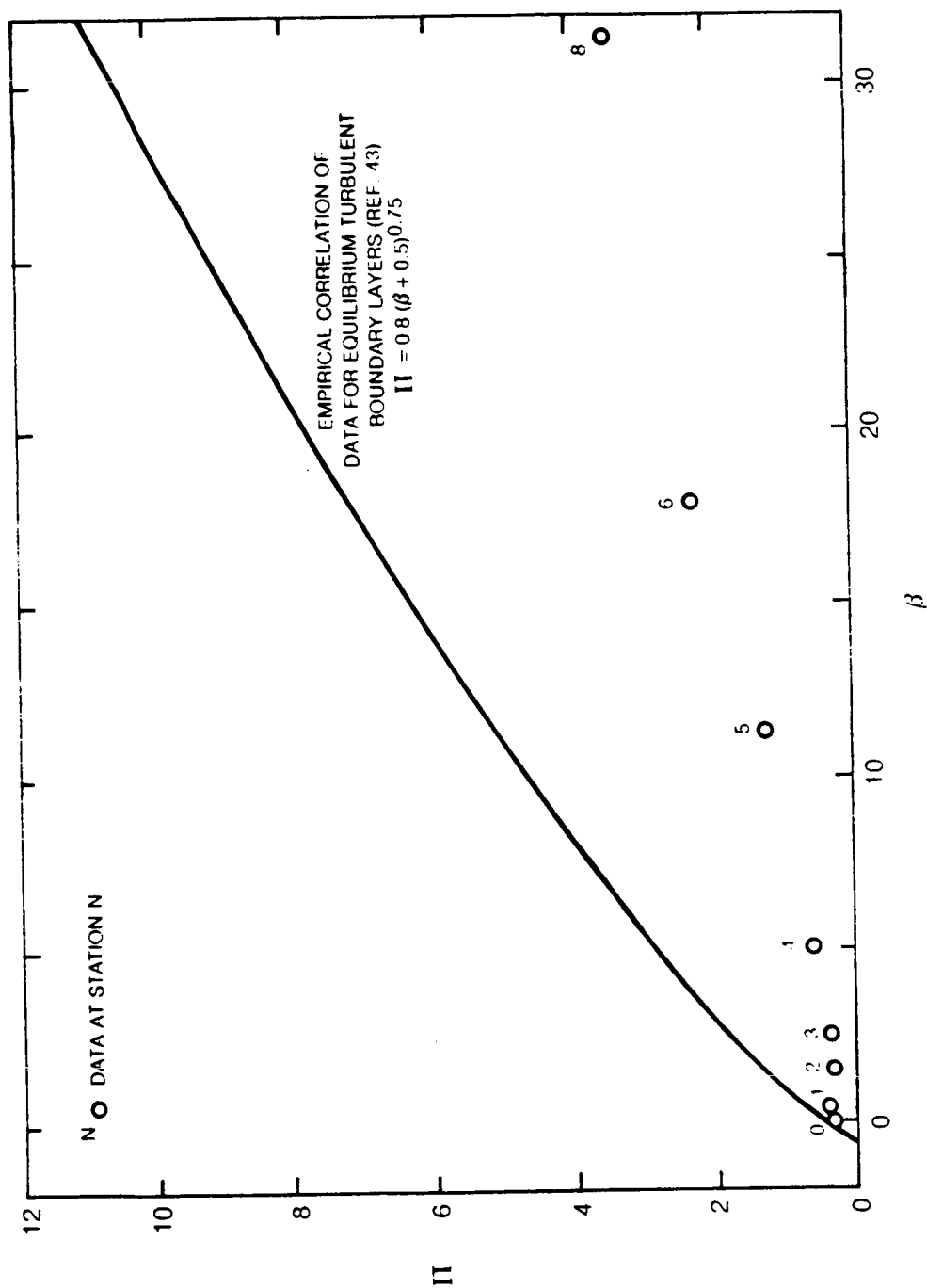


Figure 5-12 Comparison of Law-of-the-Wall Wake Parameter, Π , with Clauser Equilibrium Parameter, β , Upstream of Separation

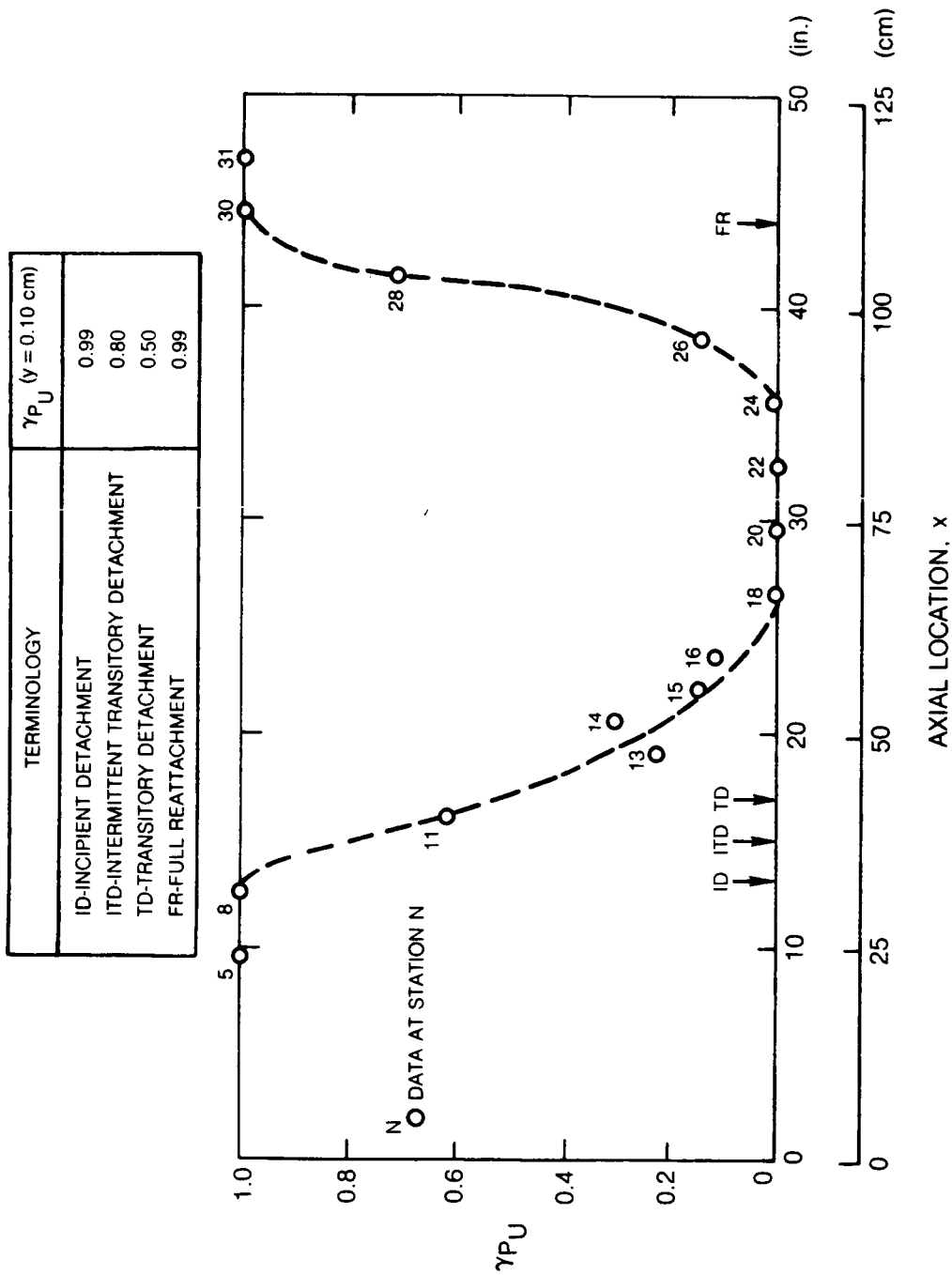


Figure 5-13 Forward Flow Fraction at $y = 0.10$ cm, $z = 0$

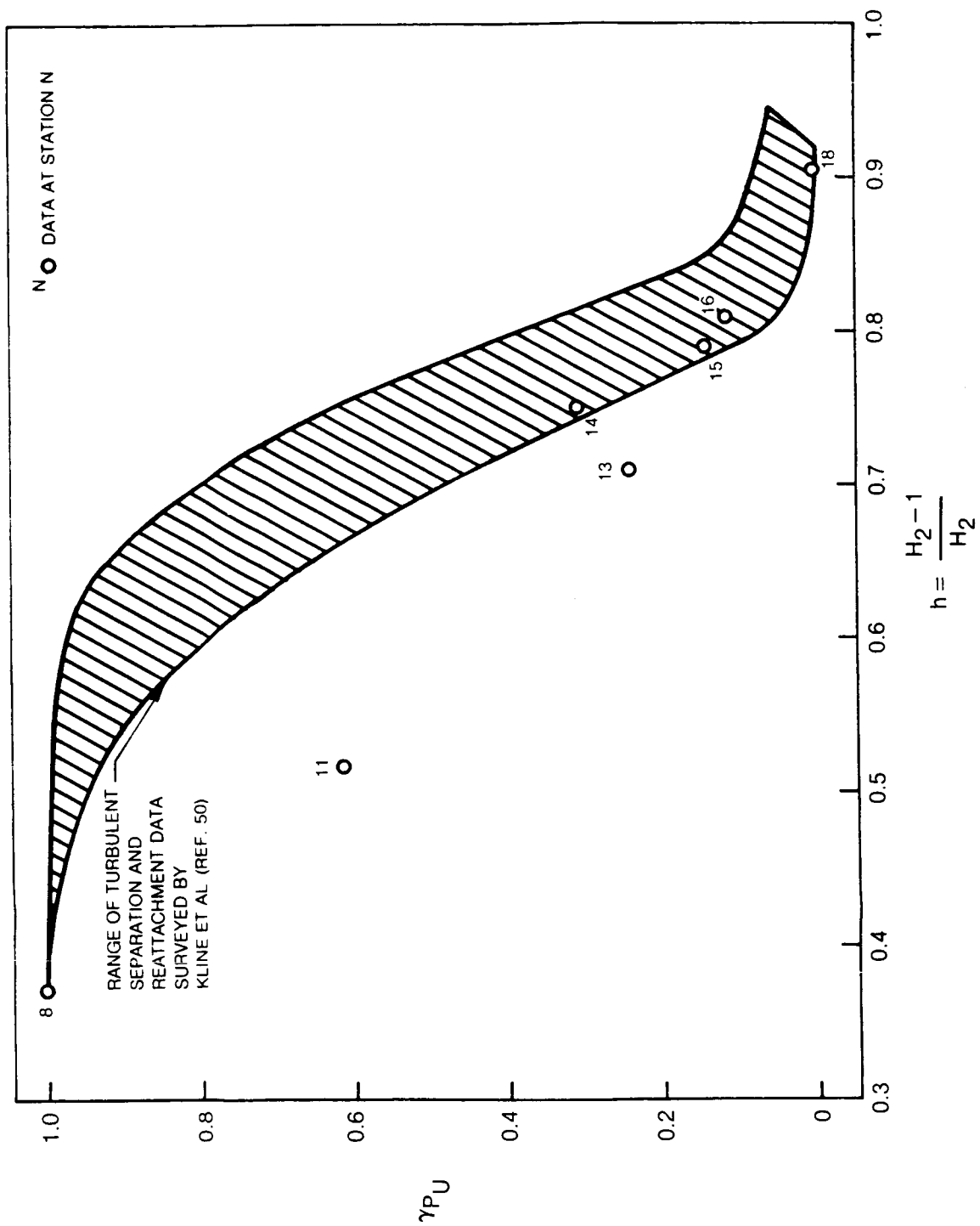


Figure 5-14 Forward Flow Fraction (γ_{PU}) vs Shape Factor (h) in Separation Region

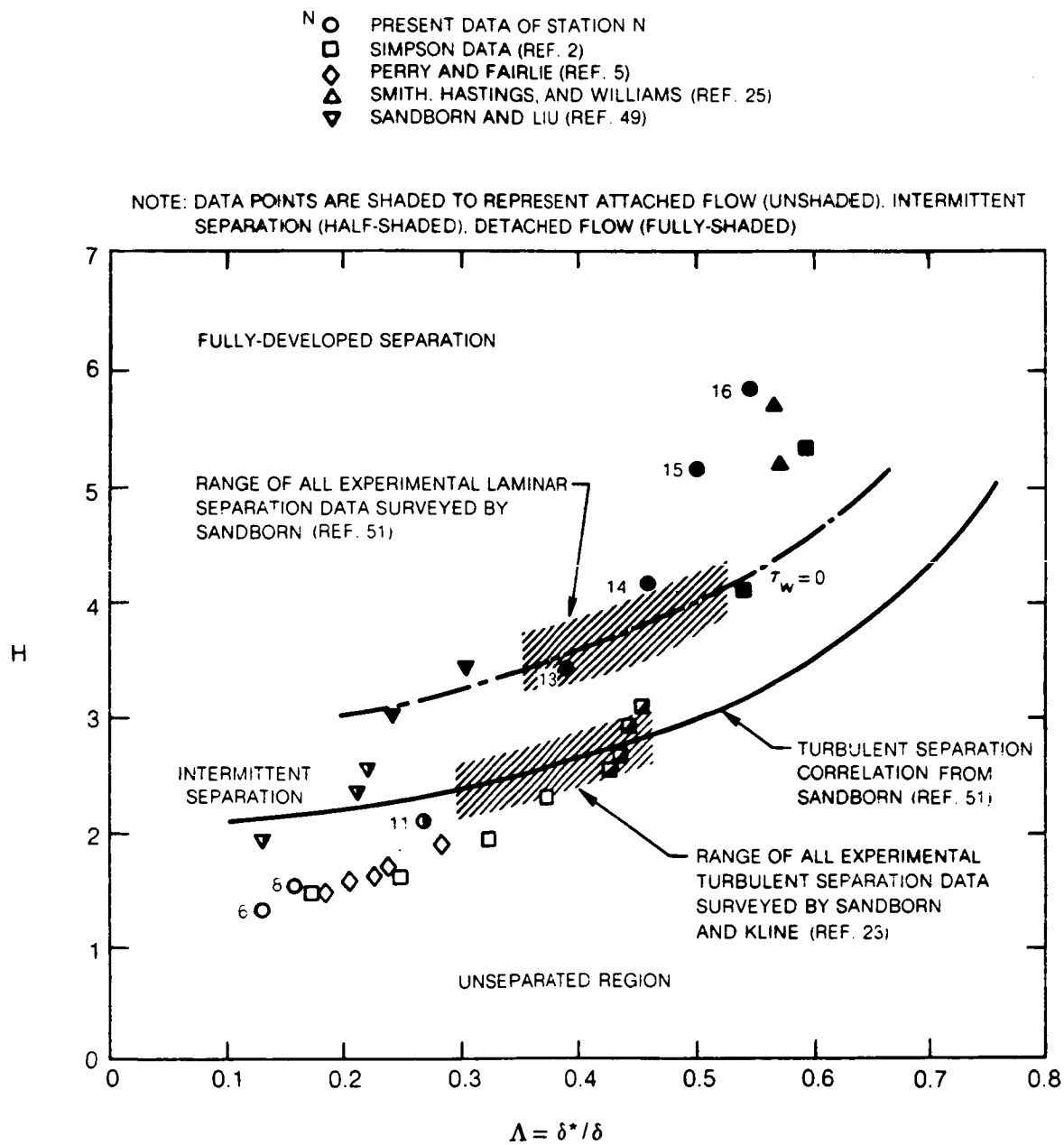


Figure 5-15 Comparison of Mean Velocity Profile Parameters at Separation with Sandborn Correlation

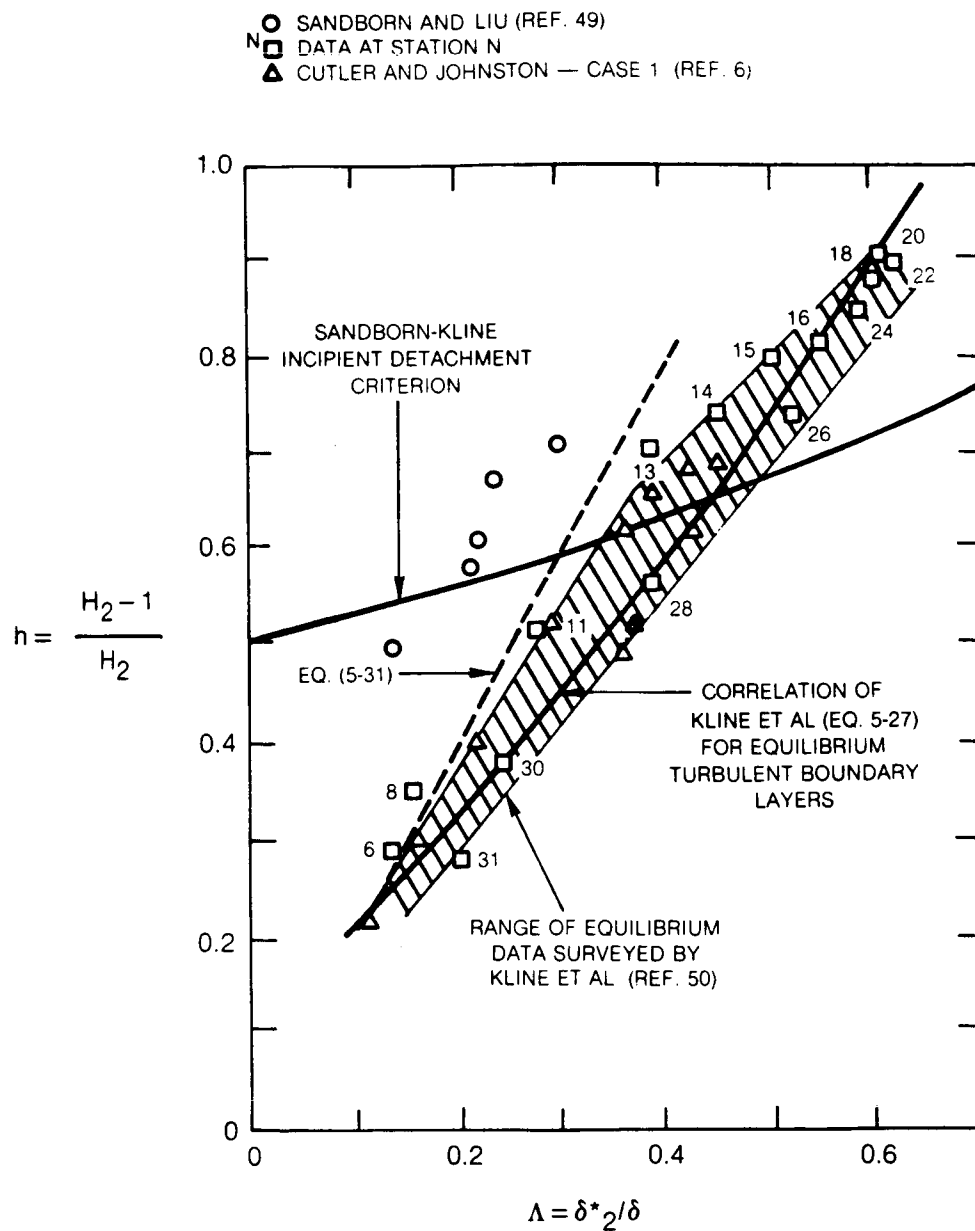
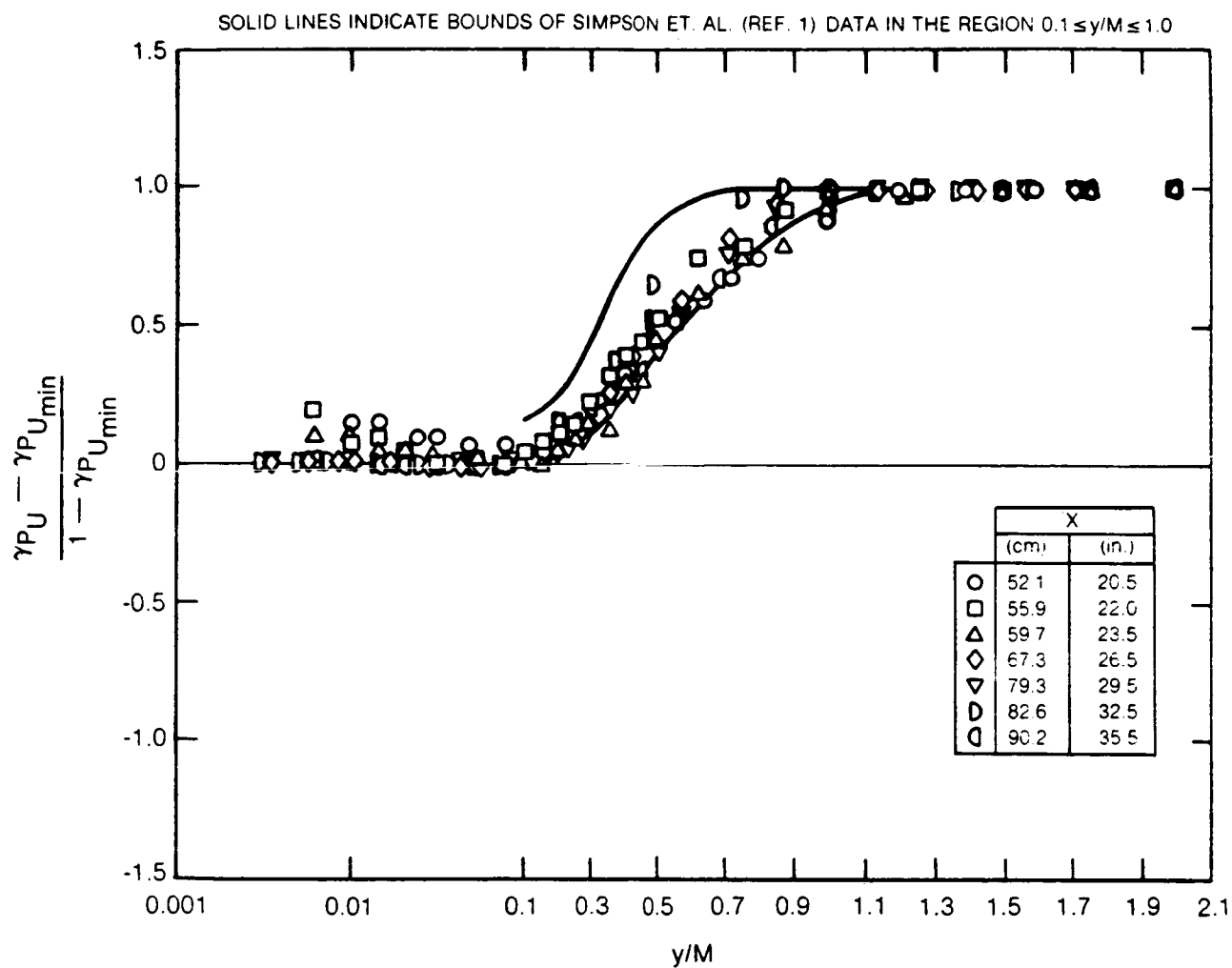


Figure 5-16. Comparison of Experimental Data to Correlation of Kline et al (ref. 50) for Attached and Separated Flows



**Figure 5-17 Normalized Forward Flow Fraction Profiles in the Separation Region
(Note Log-Linear Abscissa)**

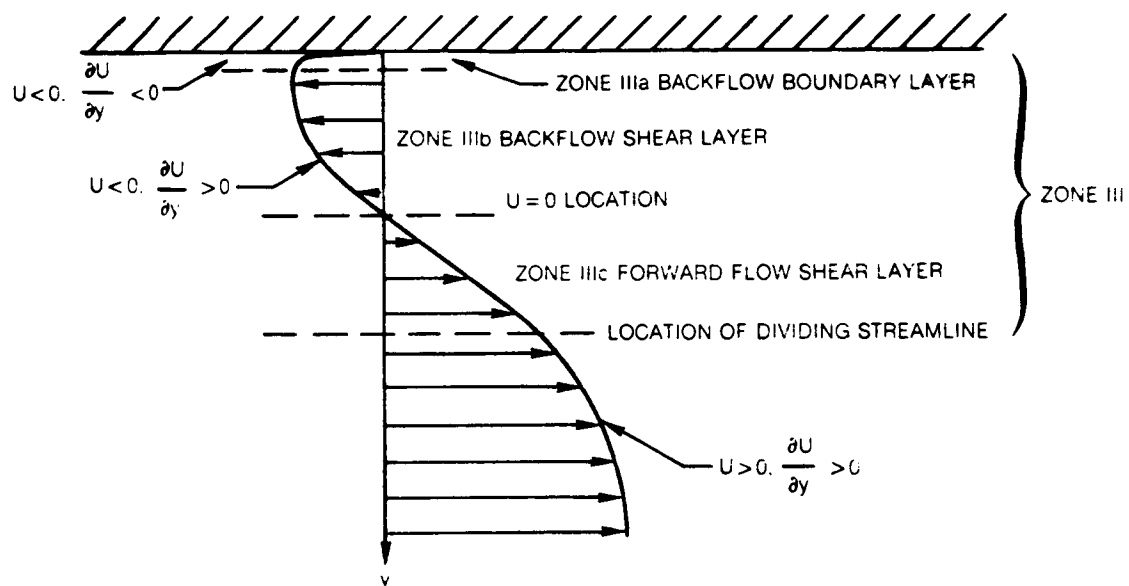


Figure 5-18 Definition of Zone III (Separation Bubble)

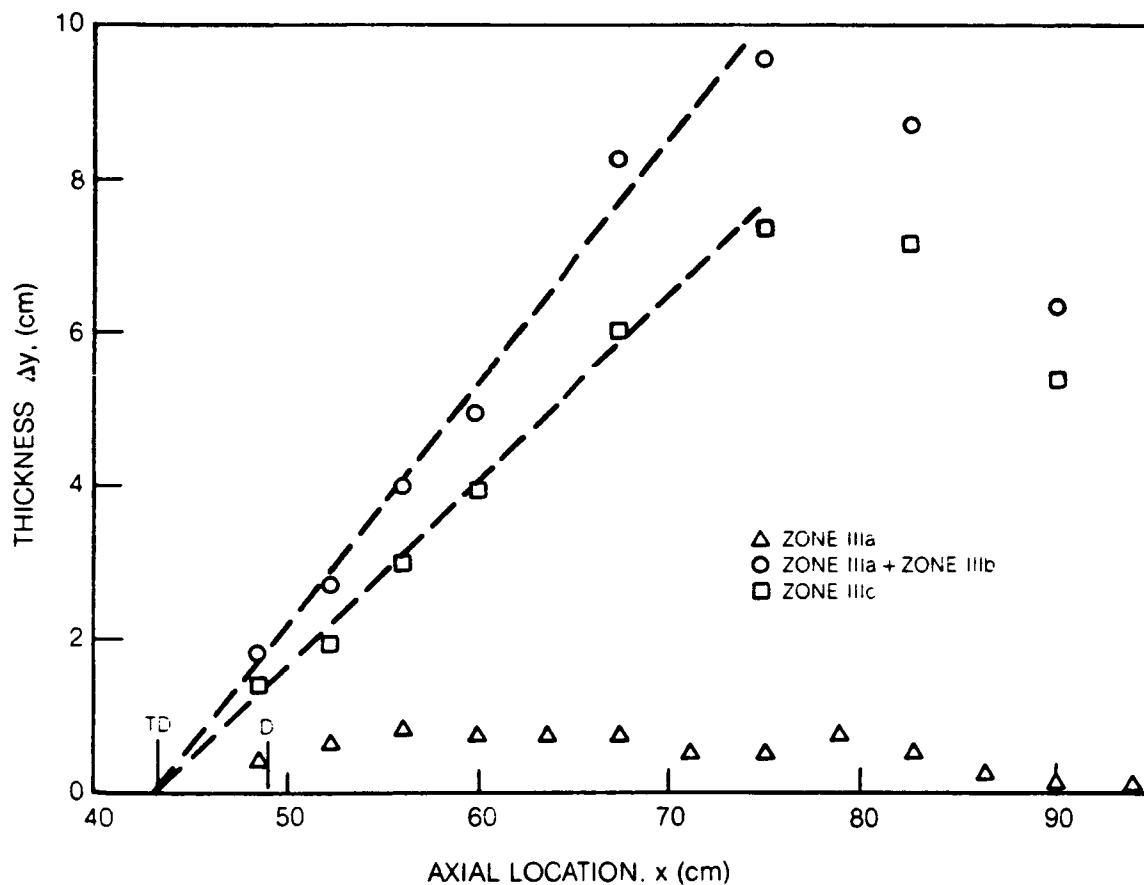


Figure 5-19 Growth of Forward-Flow and Backflow Regions within Separation Bubble

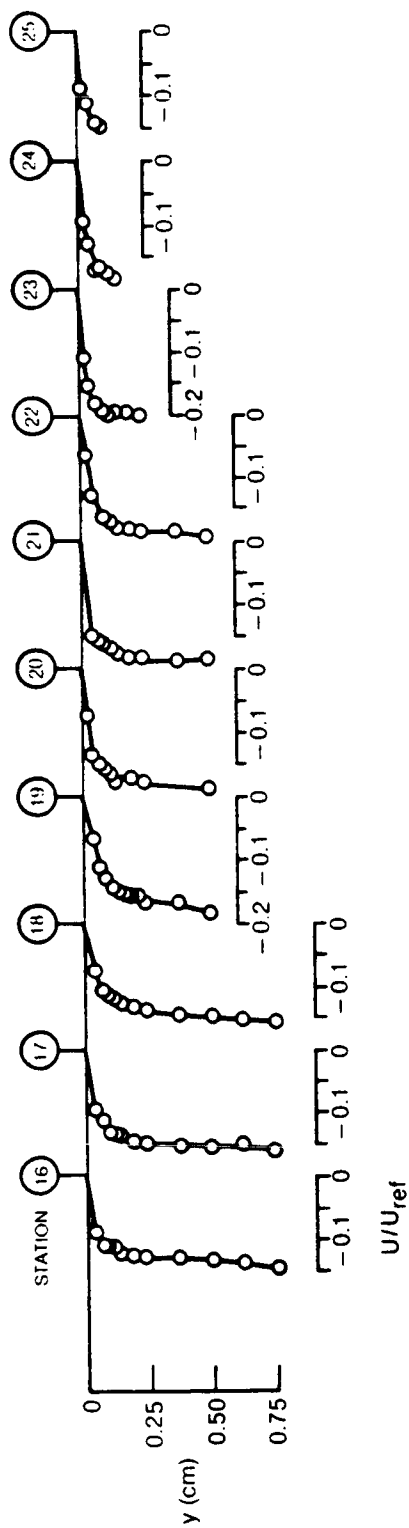


Figure 5-20 Backflow Boundary Layer Velocity Profiles Determined from Pitot Measurements

STATION NO.	x (cm)	N (cm)
○ 16	59.7	0.76
□ 18	67.3	0.76
▴ 20	74.9	0.50
△ 22	82.6	0.50
D 24	90.2	0.15

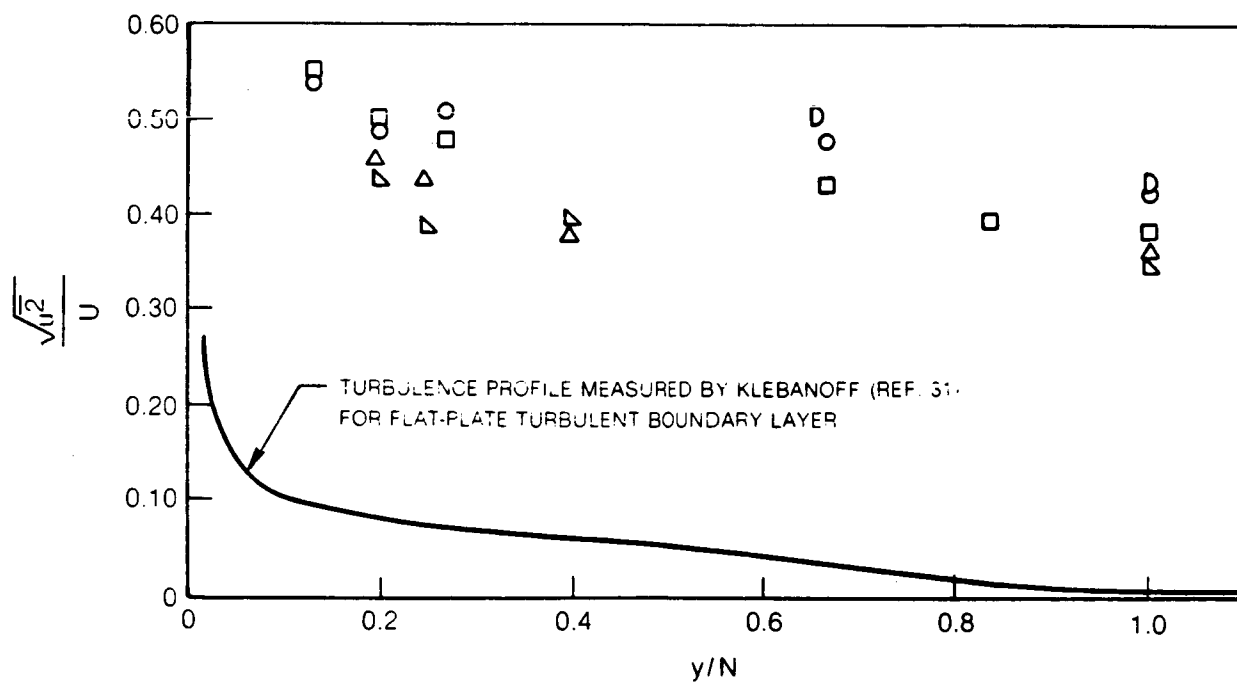


Figure 5-21 Local Axial Turbulence Levels in Backflow Boundary Layer

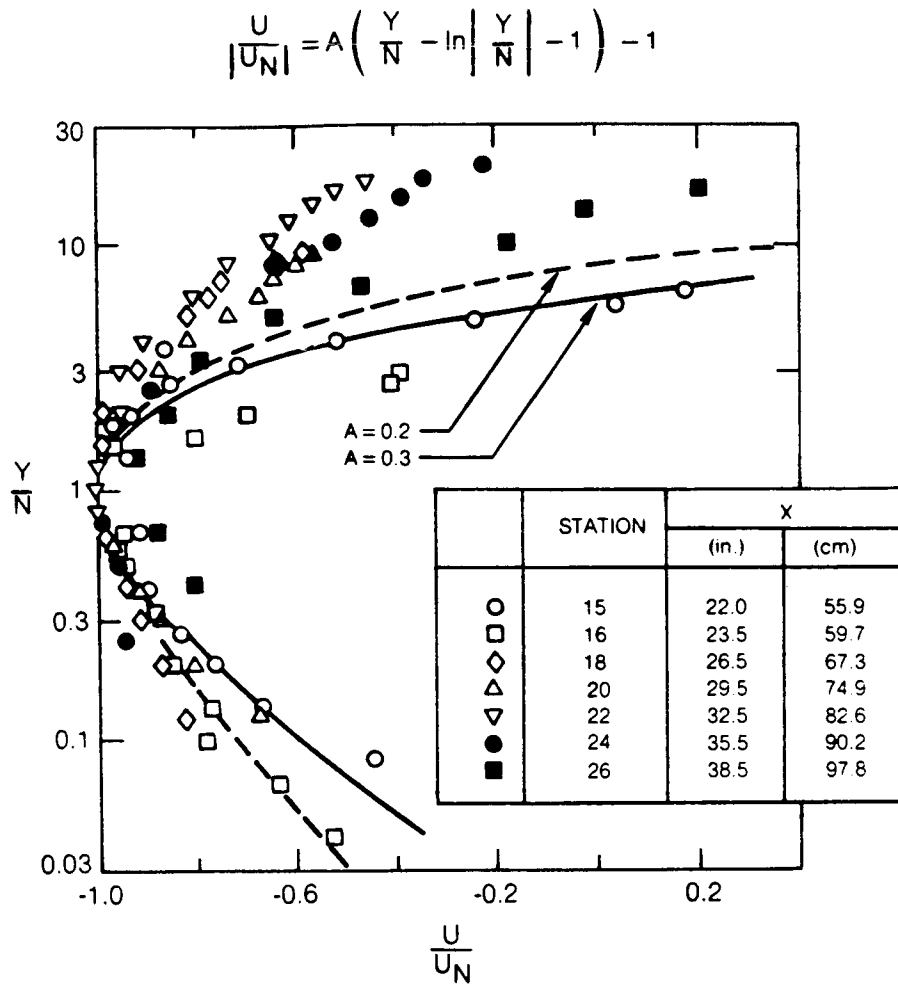


Figure 5-22 Comparison of Mean Backflow Velocity Profiles with Simpson Correlation (ref. 26)

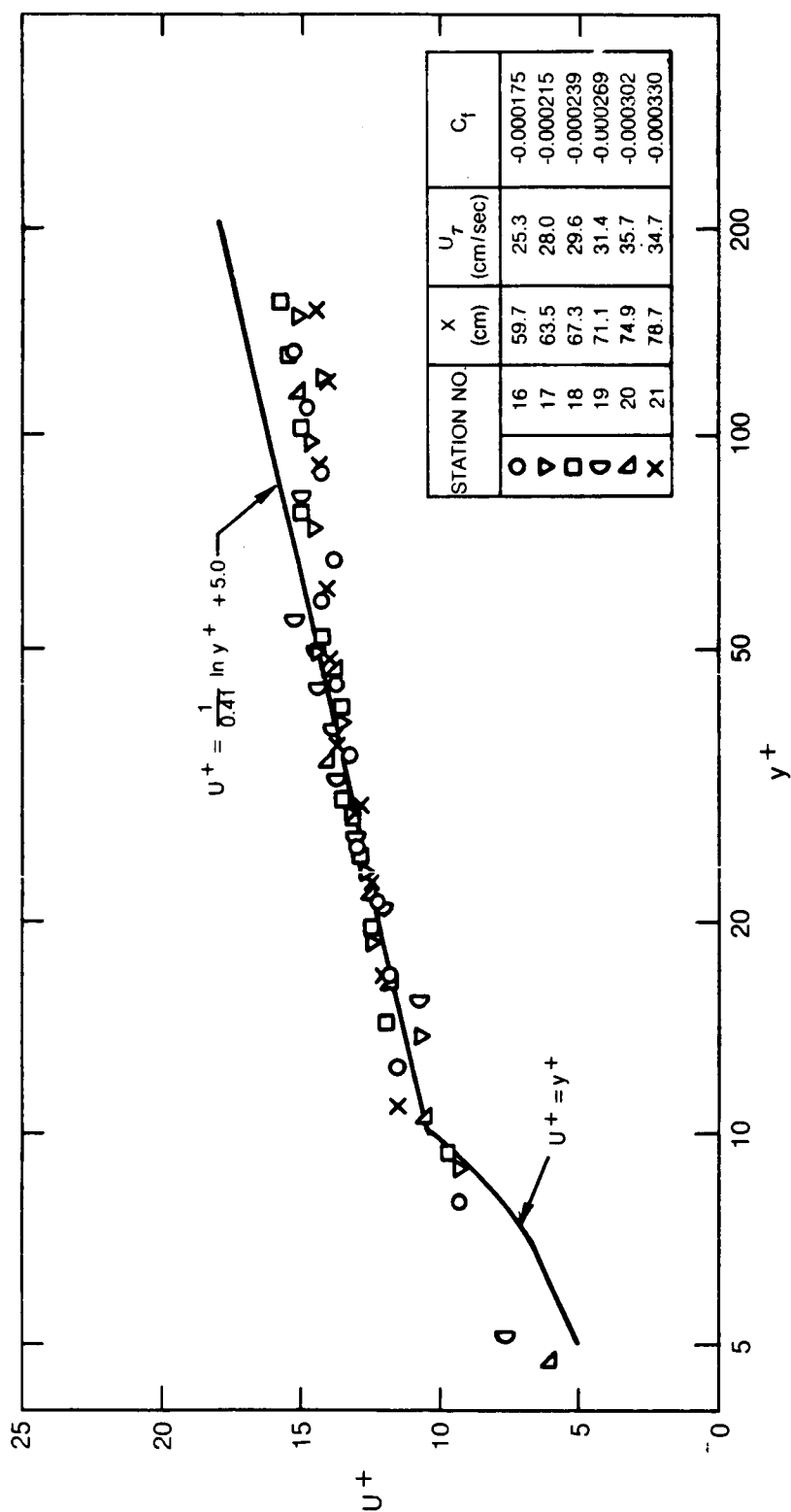


Figure 5-23 Backflow Velocity Profiles Plotted in Law-of-the-Wall Coordinates

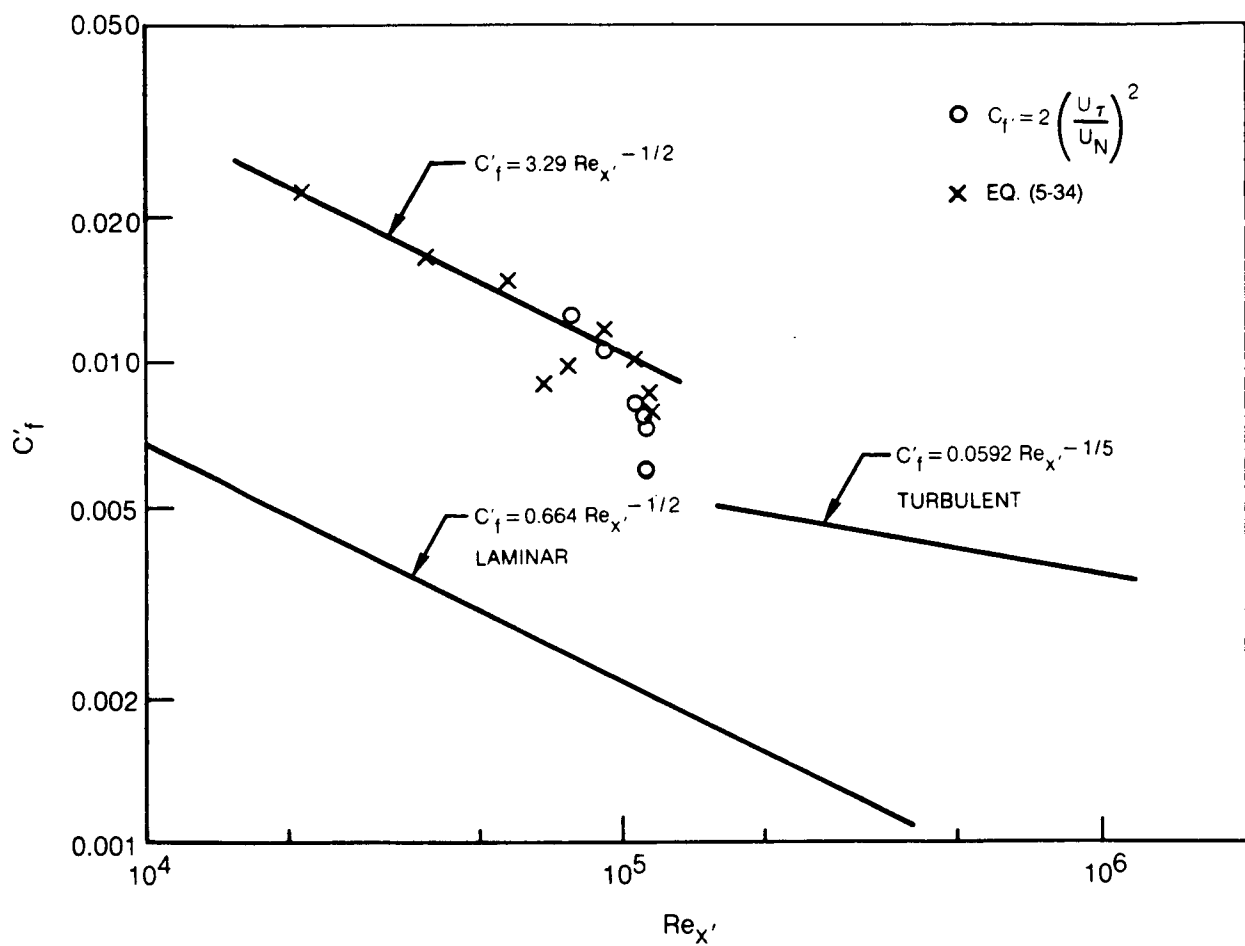


Figure 5-24 Skin Friction Coefficient in Backflow Boundary Layer

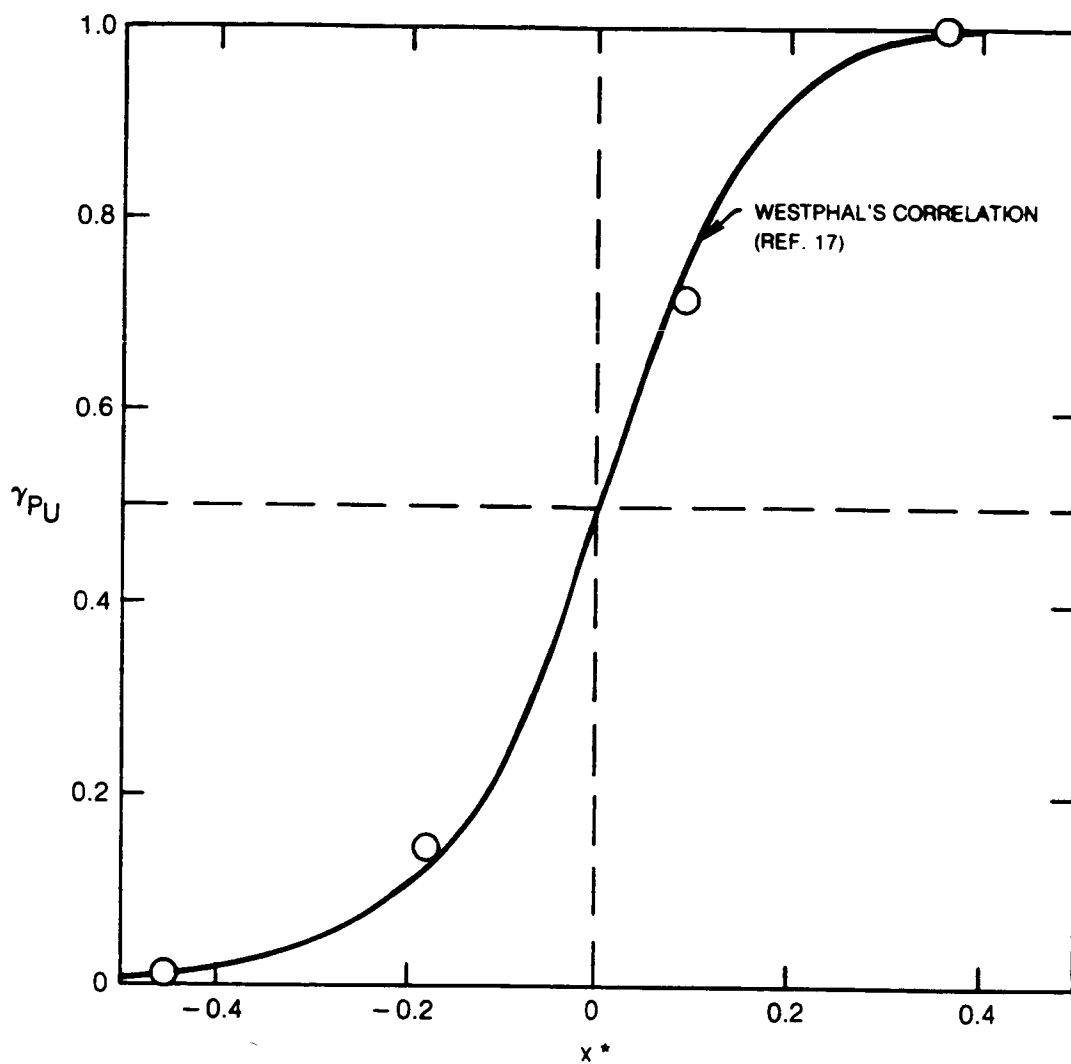


Figure 5-25 Forward Flow Fraction at $y = 0.10$ cm in Reattachment Region

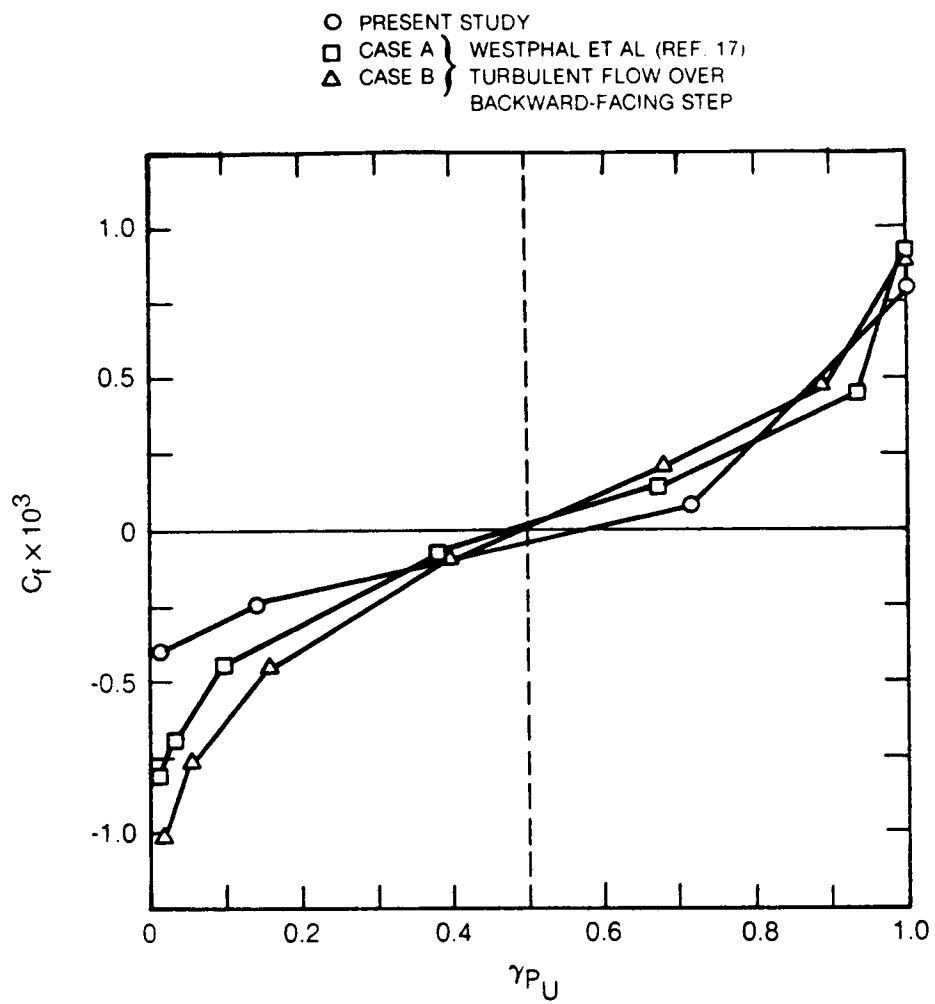


Figure 5-26 Skin Friction Coefficient vs Forward Flow Fraction Near Reattachment

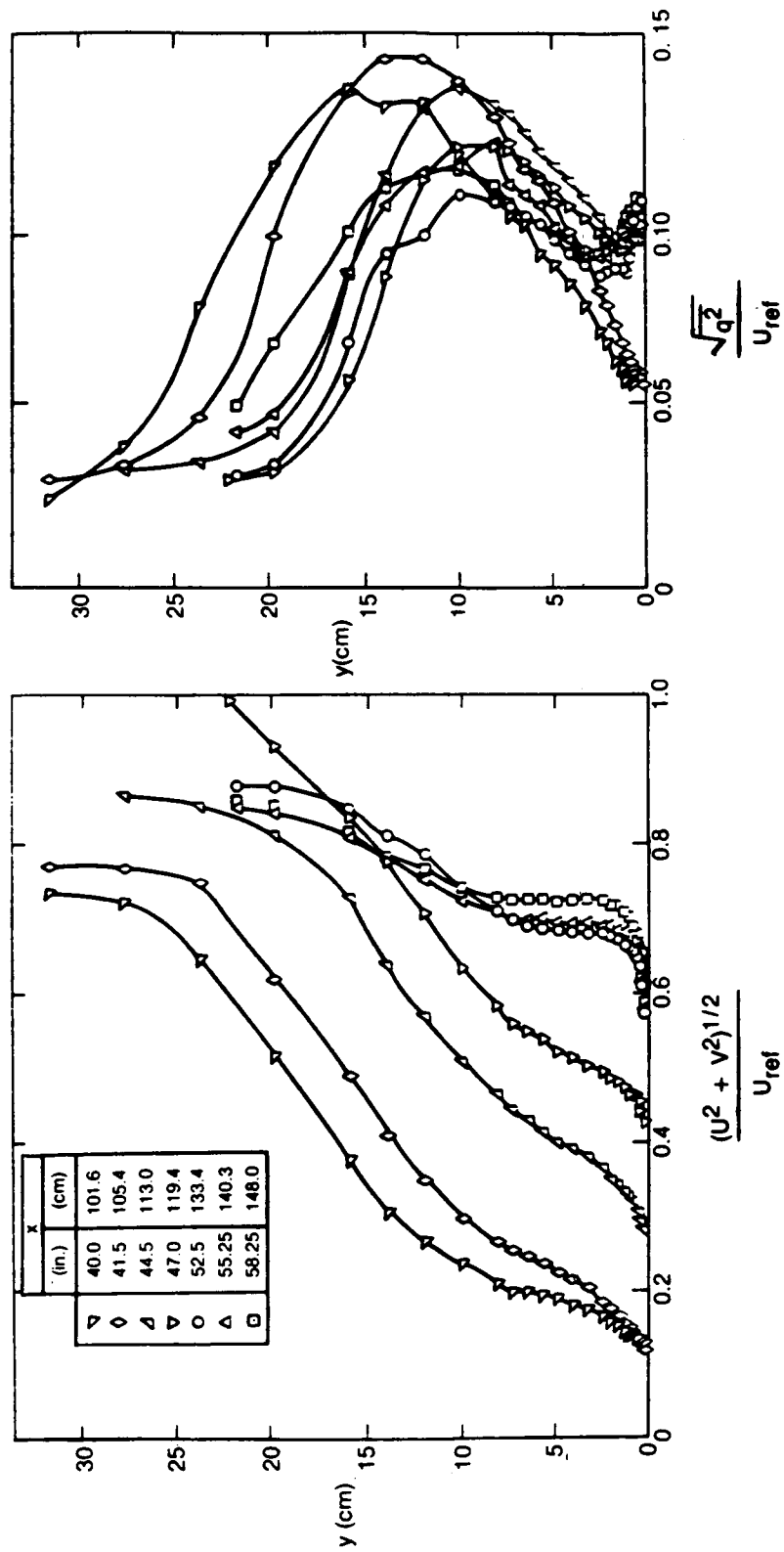


Figure 5-27 Streamwise Velocity and Turbulence Profiles Downstream of Reattachment

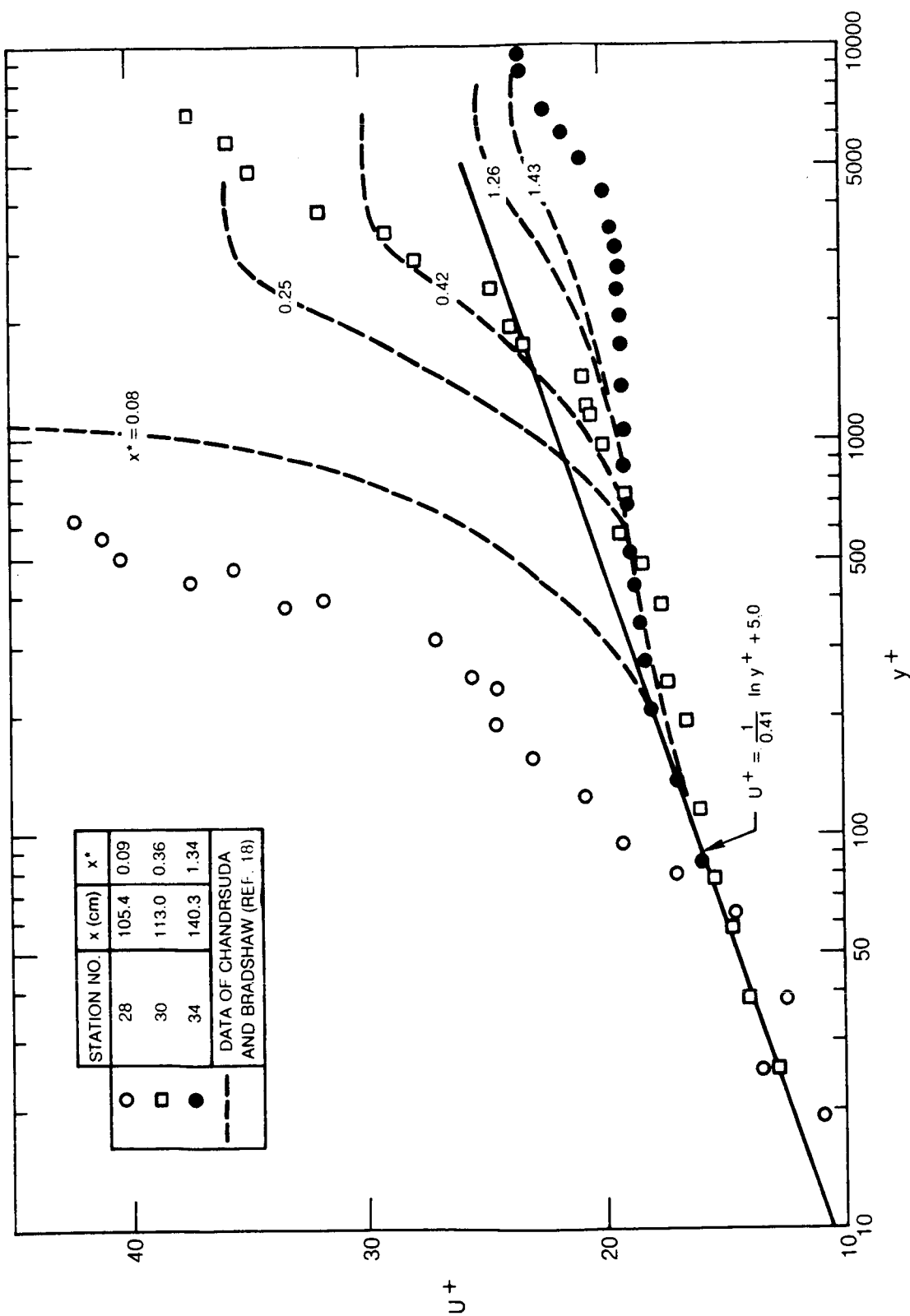


Figure 5-28 Comparison of Law-of-the-Wall Plots in Reattachment and Recovery with Data of Chandrsuda and Bradshaw (ref. 18)

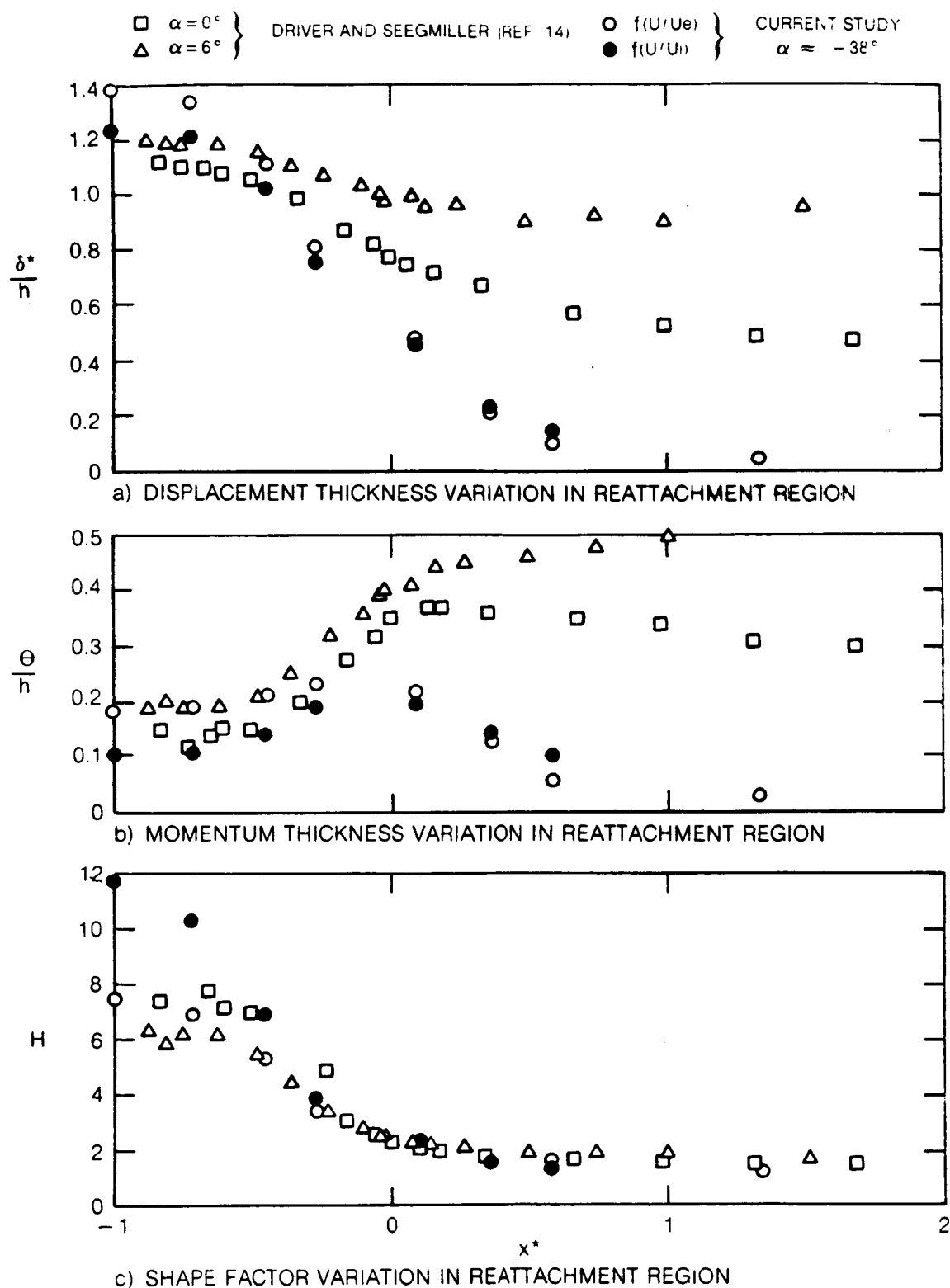
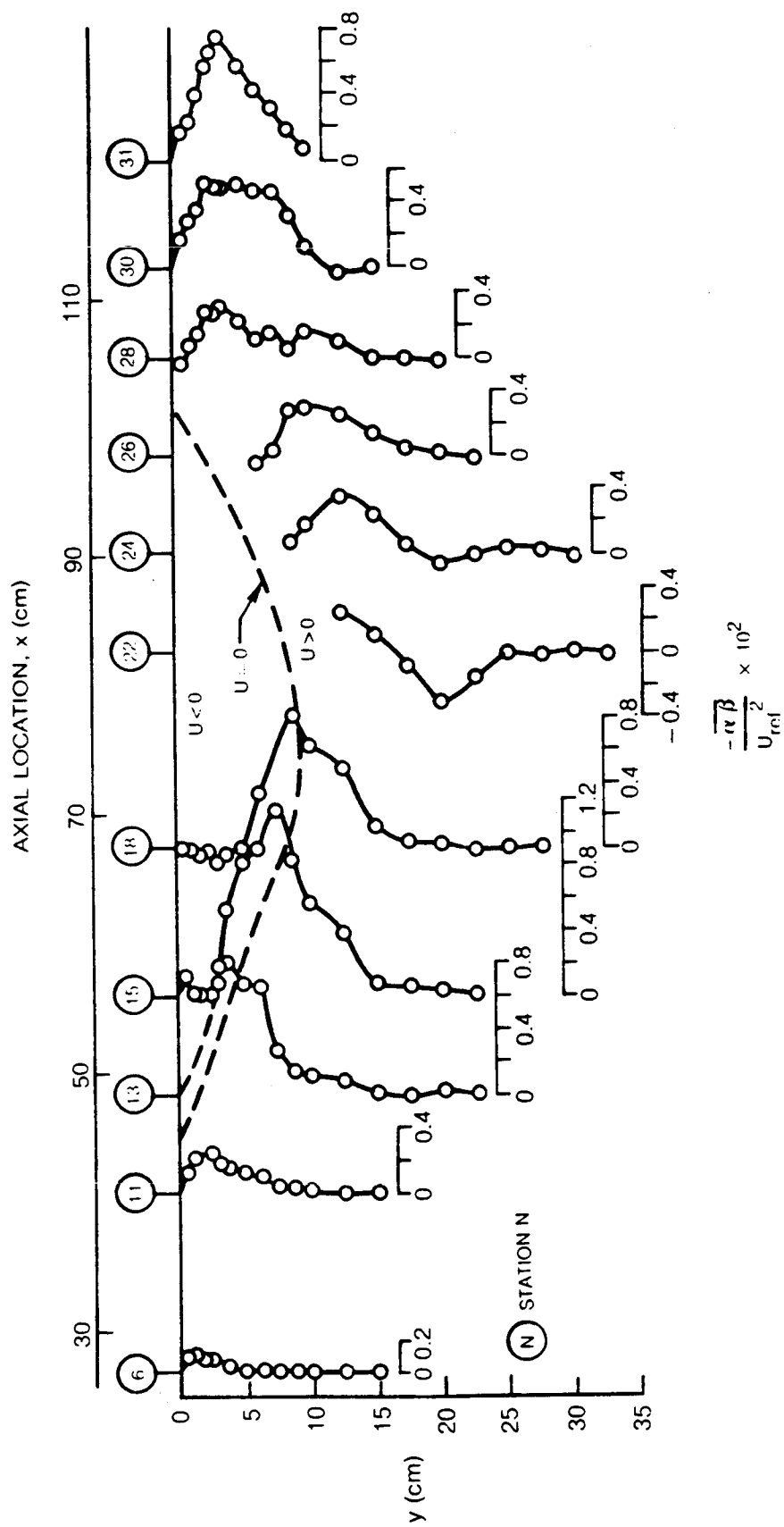


Figure 5-29 Comparison of Boundary Layer Integral Quantities in Reattachment Region with Data of Driver and Seegmiller (ref. 14)



CHAPTER 6

CONCLUSIONS

Overall conclusions and observations regarding the nature of the separated flowfield investigated in the current study are summarized here. Following these general remarks are more specific comments regarding flow in the various zones which comprised the overall flowfield.

The wind tunnel test configuration employed here produced a large scale (55 cm. axial extent, 17 cm. maximum thickness) closed separation bubble on a flat plate test surface with an incident near-equilibrium turbulent boundary layer. Based on flow visualization and spanwise flowfield measurements, the separated flowfield is concluded to be a good approximation to an idealized two-dimensional flow with separation and reattachment and hence a suitable reference case for assessing computational procedures used to predict two-dimensional separated flow phenomena. With regard to flowfield steadiness, an outer inviscid zone was defined in which velocity fluctuation levels were low (approximately two percent of the reference inlet velocity). From this low level it was concluded that the overall wind tunnel test section flow was steady although high levels of unsteadiness were obtained within certain viscously dominated flow zones. Lack of periodicity in the unsteady velocity signal suggests that the intermittent separation and unsteady reattachment process were not linked by a discrete frequency feedback loop mechanism.

As discussed in more detail below, the separated flow region at the forward end of the bubble was found to be generally similar to that obtained in previous open separation studies (turbulent separation without reattachment). While this could be expected, an unanticipated result was that the reattaching flow at the aft end of the bubble bore many similarities to reattaching flows downstream of backward facing steps. In addition to these results regarding the forward and aft end of the separation bubble, important features were identified in the near wall and outer flow regions. A reverse flowing boundary layer was identified at the base of the bubble and the flow around the bubble was found to be basically inviscid and rotational. Congruence of velocity profiles was obtained in this outer flow region supporting a similar observation in a previous separated flow study with a different test geometry.

For the purpose of providing a more detailed analysis of the various flowfield phenomena encountered here it was found that the overall flow could be conveniently divided into eight flow zones. Observations and conclusions for these various zones are given below:

Zone I - Attached Flow Region - Flow in this incident boundary layer region consisted of a near equilibrium turbulent boundary layer which lost its equilibrium structure when it encountered a strong adverse pressure gradient.

Zone II - Intermittent Separation Region - Flow in this region experienced an increasingly adverse pressure gradient causing detachment to occur within a distance equal to one incident boundary layer thickness downstream from incipient detachment. Detachment occurred at a shape factor, H , of 2.2 in line with established separation criterion, although the boundary layer did not track the $(H-1)/H$ vs. δ^*/δ (i.e. displacement thickness/boundary layer thickness) curve established by Kline et. al. (ref. 50) for equilibrium separation.

Zone III - Separation Bubble - This zone, defined as the region between the mean dividing streamline and the test surface, consisted of three sub-regions: a backflow boundary layer (Zone IIIA) at the base of the bubble, a backflow shear layer (Zone IIIB), and a forward flow shear layer (Zone IIIC). The backflow shear layer which is approximately an order of magnitude thicker than Zone IIIA, consists of an inner layer (Zone IIIB1), having a relatively flat velocity profile and a constant turbulence level approximating 8 percent of the inlet freestream velocity, which connected to viscous near wall region to the outer backflow region (Zone IIIB2) which was part of the outer shear flow. The forward flow shear layer, Zone IIIC, defined as the locus of $U = 0$ points and the dividing streamline, contained higher velocity gradients and turbulence levels than Zone IIIB. Zone IIIC was slightly thinner than the combined thicknesses of the backflow zones (Zones IIIA and Zone IIIB). The thicknesses of the backflow zones and the forward flow shear layer (Zone IIIC) increased linearly over the upstream half of the bubble from the point of transitory detachment.

Although the three-layer backflow structure defined by Zones IIIA, IIIB1, and IIIB2 agrees with the model proposed by Simpson (ref. 1), the backflow velocity profiles only matched his "universal" backflow profile (ref. 26) in the intermittent flow region just downstream of detachment. This lack of correlation can be attributed to the vigorous backflow within the closed separation bubble driven by the static pressure peak at reattachment. A large region of steady backflow, wherein the LV data indicated flow in the upstream direction 100 percent of the time, existed near the test surface over the central 35 percent of the axial extent of the bubble.

Significant normal static pressure gradients existed within the boundary layer in the vicinity of the separation bubble due to streamline curvature induced by bubble blockage. Changes in the blockage, measured by the displacement thickness, which exceeded 20 cm at the maximum bubble thickness, caused convex streamline curvature at separation and at reattachment and

concave curvature over the central part of the bubble. The resulting static pressure field was calculated from measured total pressures and LV velocity data.

The inclusion of the normal static pressure changes, which were as large as 50 percent of the dynamic head between the test surface and the lower wall near the location of the maximum bubble thickness, was found to be very important. Integral properties were calculated three ways: (1) the classical definition based on the boundary layer edge velocity, (2) a pressure-based definition which calculated the retardation of the boundary layer relative to an equivalent inviscid field determined from the measured upstream total pressure and the local derived (from measurements) static pressure, and (3) the true definition (refs. 38 and 39) which was equivalent to the classical definition with the addition of correction terms to account for the normal static pressure gradient effects. These effects were especially evident at the location of the maximum bubble thickness where the shape factor, H , was calculated to be 16.1, 11.8, and 7.5 based upon the true, pressure-based, and classical definitions, respectively.

Because of the large streamline inclination angles trends in the turbulent shear stress measurements were not evident until the measurements obtained in a coordinate system orthogonal to the test surface were rotated into a coordinate system orthogonal to the local streamline direction. High values of the resulting streamwise shear stress, indicative of strong turbulence generation, were measured near the edge of the backflow region (i.e., near the locus of $U = 0$ points) over the forward half of the bubble. Downstream of the maximum bubble thickness, the peaks broadened, decayed, and moved away from the $U = 0$ line into the wake of the bubble.

Zone IIIA - Backflow Boundary Layer - The region at the base of the separation bubble is a highly unsteady laminar boundary layer having pseudo-turbulent characteristics. The backflow velocity profiles had a limited logarithmic region with no wake component when plotted in law-of-the-wall coordinates. Skin friction coefficients derived from the law-of-the-wall plots (and corroborated by shear stress estimated from the normal velocity gradient at the wall) were approximately 100 percent higher than skin friction coefficients previously reported for intermittent backflow under open separation bubbles. The measured skin friction coefficient showed the $Re_x^{-1/2}$ dependence (where x' is distance upstream from reattachment) typical of laminar boundary layers but was 400 percent higher than values anticipated for flat-plate zero-pressure-gradient boundary layers. Some of the increased shear stress is due to the favorable pressure gradient experienced by the backflow boundary layer as it moves upstream from the static pressure peak at reattachment. It is conjectured, however, that the majority of the increase can be attributed to the effect of low frequency (i.e., length scales on the

order of the bubble size) turbulence in the bubble which is typically 40 percent of the maximum backflow velocity.

Zone IV - Reattachment Zone - In this zone the reattaching flow impinges steeply onto the test surface causing a static pressure peak which drives the strong backflow within the separation bubble. The highly unsteady flow in this zone is characterized by random low frequency streamline flapping with large scale eddies being convected alternately upstream and downstream from the impingement point on the test surface. The forward flow fraction measured near the test surface, when plotted vs. non-dimensional distance from reattachment, matches the correlation of Westphal et al. (ref. 17) for reattaching backward-facing step flows. The appropriate length scale for closed separation bubble data is the distance from the maximum bubble thickness, $x_{\delta^*_{\max}}$, to reattachment. In addition, skin friction correlated with forward flow fraction in Zone IV in the present study in the same manner as the backward-facing step data measured by Westphal et. al. (ref. 17).

Zone V - Redeveloping Near Wall Flow - This zone encompasses the near wall region downstream of reattachment where a new boundary layer begins to develop along the test surface. The boundary layer, which has high turbulence levels impressed upon it from the bubble wake, quickly develops a log-linear velocity profile near the wall and begins to merge with Zone VI, the relaxing outer shear layer, to obtain the wake-like structure of an equilibrium turbulent boundary layer.

Zone VI - Relaxing Outer Shear Layer - The free shear layer in this zone originated near the mean dividing streamline surrounding the bubble and was shed into the bubble wake. It contains relatively large length-scale, high intensity turbulence. This relaxing outer shear layer merges with the redeveloping near wall flow (Zone V) and begins an exchange of energy which eventually would lead to the development of an equilibrium turbulent profile given a sufficiently long test section. In the current study, law-of-the-wall plots of the merged boundary layer (Zones V and VI) contained negative wake components characteristics of reattaching flows. The data correlated well with the profiles of Chandrsuda and Bradshaw (ref. 18) when $x_{\delta^*_{\max}} - x_R$ was used to non-dimensionalize the axial distance downstream from reattachment where x_R was the axial location at reattachment. It is estimated that 3.75 bubble lengths downstream of reattachment, which exceeded the test section length, would have been required to eliminate the negative wake.

Zone VII - Invariant Outer Flowfield - The flow in this zone is inviscid but rotational. Velocity profiles in this region are congruent over the axial extent of the bubble when static pressure variations associated with streamline curvature are accounted for. In effect, the outer 80 percent of the

incident boundary layer is convected unaltered over the blockage associated with the inner viscously dominated bubble recirculation region. The identification of this feature of the velocity profile development appears to have important implications for the numerical modeling of the flow.

REFERENCES

1. Simpson, R. L., J. H. Strickland and P. W. Barr: Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation, J. Fluid Mechanics, vol. 79, pt. 3, 1977, pp. 553-594.
2. Simpson, R. L., Y.-T. Chew and B. G. Shivaprasad: The Structure of a Separating Turbulent Boundary Layer. Part 1. Mean Flow and Reynolds Stresses, J. Fluid Mechanics, vol. 113, 1981, pp. 23-51.
3. Simpson, R. L., Y.-T. Chew and B. G. Shivaprasad: The Structure of a Separating Turbulent Boundary Layer. Part 2. Higher-Order Turbulence Results, J. Fluid Mechanics, vol. 113, 1981, pp. 53-73.
4. Shiloh, K., B. G. Shivaprasad and R. L. Simpson: The Structure of a Separating Turbulent Boundary Layer. Part 3. Transverse Velocity Measurements, J. Fluid Mechanics, vol. 113, 1981, pp. 75-90.
5. Perry, A. E., and B. D. Fairlie: A Study of Turbulent Boundary-Layer Separation and Reattachment, J. Fluid Mechanics, vol. 69, pt. 4, 1975, pp. 657-672.
6. Cutler, A. D. and J. P. Johnston: Adverse Pressure Gradient and Separating Turbulent Boundary-Layer Flows: The Effect of Disequilibrium in Initial Conditions, Rept. MD-46, Thermo-Sciences Div., Mechanical Engineering Dept., Stanford University, October 1984.
7. Kline, S. J., J. H. Ferziger, and J. P. Johnston: Opinion - The Calculation of Turbulent Shear Flows: Status and Ten-Year Outlook, Trans. ASME, J. Fluids Eng., vol. 100, 1978, pp. 3-5.
8. Simpson, R. L.: REVIEW - A Review of Some Phenomena in Turbulent Flow Separation, Trans. ASME, J. of Fluids Engineering, vol. 103, December 1981, pp. 520-533.
9. Simpson, R. L.: Summary Report on the Colloquium on Flow Separation, Project SQUID Rept. SMU-3-PU, 1979.
10. Mueller, T. J.: On Separation, Reattachment, and Redevelopment of Turbulent Boundary Layers, Ph.D. Thesis, Dept. of Mechanical Engineering, University of Illinois, 1961.

REFERENCES (Cont'd)

11. Bradshaw, P. and F. Y. F. Wong: The Reattachment and Relaxation of a Turbulent Shear Layer, J. Fluid Mechanics, vol. 52, pt. 1, 1972, pp. 113-135.
12. Eaton, J. K. and J. P. Johnston: A Review of Research on Subsonic Turbulent Flow Reattachment, AIAA J., vol. 19, no. 9, September 1981, pp. 1093-1100.
13. Kim, J., S. J. Kline and J. P. Johnston: Investigation of a Reattaching Turbulent Shear Layer: Flow Over a Backward-Facing Step, Trans. ASME, J. of Fluids Eng., vol. 102, September 1980, pp. 302-308.
14. Driver, D. M. and H. L. Seegmiller: Features of a Reattaching Turbulent Shear Layer Subject to an Adverse Pressure Gradient, AIAA Paper 82-1029, June 1982.
15. Armaly, B. F., F. Durst and R. Schönung: Measurements and Predictions of Flow Downstream of a Two-Dimensional Single Backward-Facing Step, Report SFB80/ET/172, Sonderforschungsbereich, Univ. of Karlsruhe, 1980.
16. Pronchick, S. W. and S. J. Kline: An Experimental Investigation of the Structure of a Turbulent Reattaching Flow Behind a Backward-Facing Step, Rept. MD-42, Thermosciences Div., Mechanical Engineering Dept., Stanford University, June 1983.
17. Westphal, R. V., J. P. Johnston and J. K. Eaton: Experimental Study of Flow-Reattachment in a Single-Sided Sudden Expansion, NASA CR 3765, January 1984.
18. Chandrsuda, C. and P. Bradshaw: Turbulence Structure of Reattaching Mixing Layer, J. Fluid Mechanics, vol. 110, pp. 171-194, 1981.
19. Ota, T. and N. Kon: Heat Transfer in the Separated and Reattached Flow on a Blunt Flat Plate, Trans. ASME, J. of Heat Transfer, November 1974, pp. 459-462.
20. Ota, T.: An Axisymmetric Separated and Reattached Flow on a Longitudinal Blunt Circular Cylinder, J. of Applied Mechanics, June 1975, pp. 311-315.
21. Ota, T. and M. Itasaka: A Separated and Reattached Flow on a Blunt Flat Plate, Trans. ASME, J. of Fluids Engineering, March 1976, pp. 79-86.

REFERENCES (Cont'd)

22. Mueller, T. J. and J. M. Robertson: A Study of Mean Motion and Turbulence Downstream of a Roughness Element, *Developments in Theoretical and Applied Mechanics*, vol. 1, 1963, pp. 326-340.
23. Sandborn, V. A., and S. J. Kline: Flow Models in Boundary-Layer Stall Inception, *Trans. ASME, J. of Basic Engineering*, September 1961, pp. 317-327.
24. Simpson, R. L.: Some Features of Two Dimensional Separated Flows, *AIAA Paper 85-0178*, January, 1985.
25. Smith P. D., R. C. Hastings and B. R. Williams: Calculation and Measurement of Separated Turbulent Boundary Layers, *RAE Technical Memorandum Aero 1955*, October 1982, (Paper presented at Euromech 148 Two-Dimensional Separated Flows, Bochum, W. Germany, 13-15, October 1981).
26. Simpson, R. L.: A Model for the Backflow Mean Velocity Profiles, *AIAA Journal*, vol. 21, no. 1, January 1983, pp. 142-143.
27. Simpson, R. L., B. G. Shivaprasad and Y.-T. Chew: The Structure of a Separating Turbulent Boundary Layer. Part 4. Effects of Periodic Free-Stream Unsteadiness, *J. Fluid Mechanics*, vol. 127, 1983, pp. 219-261.
28. Blair, M. F., D. A. Bailey, and R. H. Schlinker: Development of a Large-Scale Wind Tunnel for the Simulation of Turbomachinery Airfoil Boundary Layers, *Trans. ASME, J. of Engineering for Power*, vol. 103, 1981, pp. 678-687.
29. Landgrebe, A. J.: An Analytical and Experimental Investigation of Helicopter Rotor Hover Performance and Wake Geometry Characteristics, *USAAMRDL Technical Report 71-24*, June 1971.
30. Coles, D. E.: The Turbulent Boundary Layer in a Compressible Fluid, *Rand Corp. Rept. R-403-PR*, September 1962.
31. Klebanoff, P. S.: Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient, *NACA Rep. No. 1247*, 1955.
32. Eaton, J. K. and J. P. Johnston: Low-frequency Unsteadiness of a Reattaching Turbulent Shear Layer, in *Turbulent Shear Flows 3; International Symposium*, 3rd, Davis, CA., Sept. 9-11, 1981, Springer-Verlag, Berlin, 1982, pp. 162-170.

REFERENCES (Cont'd)

33. Cherry, N. J., R. Hillier, and M. E. M. P. Latour: Unsteady Measurements in a Separated and Reattaching Flow, J. Fluid Mechanics, vol. 144, 1984, pp. 13-46.
34. Mabey, D. G.: Pressure Fluctuations Caused by Separated Bubble Flows at Subsonic Speeds, RAE Technical Report 71160 ref. Aero 3204, August 1971.
35. Schlichting, H.: Boundary Layer Theory. Fourth ed. McGraw-Hill, Inc., 1962.
36. Paterson, R. W. and H. D. Weingold: Experimental Investigation of a Simulated Compressor Trailing-Edge Flowfield, AIAA J., vol. 23, no. 5, May 1985, pp. 768-775.
37. Patrick, W. P.: Error Analysis for Benchmark Fluid Dynamic Experiments, Part I: Error Analysis Methodology and the Quantification of Laser Velocimeter Error Sources, United Technologies Research Center Rept. R85-151772, 1985.
38. Kiock, R.: Evaluation of Boundary Layer Measurements in Two-Dimensional Compressible Subsonic Flow with a Pressure Gradient across the Boundary Layer, European Space Agency Technical Translation, ESA-TT-810, July 1983.
39. Kooi, J. W.: Influence of Free-Stream Mach Number on Transonic Shock-Wave Boundary-Layer Interaction, Rept. No. NLR MP 78013 U, National Aerospace Laboratory, Amsterdam, The Netherlands, May 23, 1978.
40. So, R. M. C., and G. L. Mellor: Experiment on Convex Curvature Effects in Turbulent Boundary Layers, J. Fluid Mechanics, vol. 60, no. 1, 1973, pp. 43-62.
41. Mayle, R. E., F. C. Kopper, M. F. Blair, and D. A. Bailey: Effect of Streamline Curvature on Film Cooling, ASME Paper No. 76-GT-96, March 1976.
42. Swafford, T. W.: Analytical Approximation of Two-Dimensional Separated Turbulent Boundary-Layer Velocity Profiles, AIAA J., vol. 21, no. 6, June 1983, pp. 923-926.

REFERENCES (Cont'd)

43. White, F. W.: Viscous Fluid Flow, McGraw-Hill Book Co., N. Y., 1974.
44. Alber, I. E., Bacon, J. W., Masson, B. S., and D. J. Collins: An Experimental Investigation of Turbulent Transonic Viscous-Inviscid Interactions, AIAA J., vol. 11, May 1973, pp. 620-627.
45. Coles, D.: The Law of the Wake in the Turbulent Boundary Layer, J. Fluid Mechanics, vol. 1, 1956. pp. 191-226.
46. Clauser, F. H.: The Turbulent Boundary Layer, in Advances in Applied Mechanics, vol. IV, Academic Press, N. Y., 1956, pp. 1-51.
47. Kline, S. J., M. V. Morkovin, G. Sovran, D. J. Cockrell, eds: Proceedings, Computation of Turbulent Boundary Layers - 1968 AFOSR-IFP-Stanford Conference, vol. 1, Thermosciences Div., Dept. of Mech. Eng., Stanford Univ., 1968.
48. Kline, S. J. and P. W. Runstadler: Some Preliminary Visual Studies of the Wall Layers of Turbulent Boundary Layers, Trans. ASME, Ser. E: J. Applied Mechanics, vol. 26, 1959, pp. 166-170.
49. Sandborn, V. A. and C. Y. Liu: On Turbulent Boundary-Layer Separation, J. Fluid Mechanics, vol. 32, pt. 2, 1968, pp. 293-304.
50. Kline, S. J., J. G. Bardina, and R. C. Strawn: Correlation of the Detachment of Two-Dimensional Turbulent Boundary Layers, AIAA J., vol. 21, no. 1, January 1983, pp. 68-73.
51. Sandborn, V. A.: An Equation for the Mean Velocity Distribution of Boundary Layers, NASA Memo 2-5-59E, 1959.
52. Kline, S. J., A. V. Lisin, and B. A. Waitman: Preliminary Experimental Investigation of Effect of Free-Stream Turbulence on Turbulent Boundary-Layer Growth, NASA TN D-368, March 1960.
53. Wagner, J.: Personal Communication, United Technologies Research Center, 1985.
54. Dyban, Y. P., E. Y. Epik, and T. T. Suprun: Characteristics of the Laminar Boundary Layer in the Presence of Elevated Free-Stream Turbulence, Fluid Mechanics - Soviet Research, vol. 5, no. 4, July-Aug. 1976, pp. 30-36.

REFERENCES (Cont'd)

55. Simpson, R. L., B. Chehroudi, and B. G. Shivaprasad: Pointwise and Scanning Laser Anemometer Measurements in Steady and Unsteady Separated Turbulent Boundary Layers, Proceedings of the International Symposium on Applications of Laser - Doppler Anemometry to Fluid Mechanics, Paper 11.3, Lisbon, Portugal, July 5-7, 1982.
56. Abernathy, R. B. and J. W. Thompson: Handbook-Uncertainty in Gas Turbine Measurements. AEDC-TR-73-5, 1973.
57. Paterson, R. W.: Turbofan Forced Mixer-Nozzle Internal Flowfield, I - A Benchmark Experimental Study. NASA CR-3492, April 1982.
58. Goldstein, S.: A Note on the Measurement of Total Head and Static Pressure in a Turbulent Stream, Proc. Roy. Soc. (London), vol. 155, 1936, p. 570.
59. Bryer, D. W. and R. C. Pankhurst: Pressure-Probe Methods for Determining Wind Speed and Flow Direction. National Physical Laboratory, H. M. Stationery Office, London, 1971.
60. Jorgenson, F. E.: Directional Sensitivity of Wire and Fiber-Film Probes - An Experimental Study. DISA Information, no. 11, May 1971, pp. 31-37.

TABLE I TRAVERSE MEASUREMENT STATIONS ON TEST SURFACE

STATION NO.	x	
	(in.)	(cm)
ref	-61.50	- 156.2
0	-9.50	- 24.1
1	1.00	2.5
2	3.00	7.6
3	5.25	13.3
4	7.50	19.1
5	9.50	24.1
6	10.50	26.7
7	11.50	29.2
8	12.50	31.8
9	13.50	34.3
10	14.50	36.8
11	16.00	40.6
12	17.50	44.5
13	19.00	48.3
14	20.50	52.1
15	22.00	55.9
16	23.50	59.7
17	25.00	63.5
18	26.50	67.3
19	28.00	71.1
20	29.50	74.9
21	31.00	78.7
22	32.50	82.6
23	34.00	86.4
24	35.50	90.2
25	37.00	94.0
26	38.50	97.8
27	40.00	101.6
28	41.50	105.4
29	43.00	109.2
30	44.50	113.0
31	47.00	119.4
32	50.00	127.0
33	52.50	133.4
34	55.25	140.3
35	58.25	148.0

STATION NO. <u>C6</u> $x = 26.7$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{PU}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{PV}
.635	.043	.496	.081	1	.004	.039	.535
1.27	.127	.567	.083	1	.013	.036	.625
1.91	.19	.629	.084	1	.022	.036	.718
2.54	.253	.686	.087	1	.03	.033	.815
3.18	.316	.75	.076	1	.04	.03	.904
3.81	.38	.8	.058	1	.058	.028	.99
5.08	.506	.872	.031	1	.072	.019	.99
6.35	.633	.901	.022	1	.082	.012	.99
7.62	.759	.919	.014	1	.096	.01	.99
8.89	.886	.931	.013	1	.1	.009	.99
10.16	1.01	.944	.012	1	.109	.01	.99
12.7	1.27	.979	.013	1	.122	.011	.99
15.24	1.52	1.014	.015	1	.134	.014	.99
17.78	1.77	1.026	.035	1			
20.32	2.03	.969	.046	1			

STATION NO. <u>C8</u> $x = 31.8$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{PU}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{PV}
.064	.006	.254	.104	1			
.102	.009	.276	.102	1			
.152	.014	.294	.099	1			
.305	.028	.346	.111	1			
.508	.046	.376	.096	1			
.635	.058	.401	.103	1	.008	.044	.557
1.27	.116	.487	.09	1	.024	.044	.692
1.91	.174	.556	.09	1	.039	.042	.826
2.54	.231	.613	.091	1			
3.18	.289	.651	.085	1	.059	.034	.95
3.81	.347	.705	.079	1	.069	.034	.978
5.08	.463	.783	.052	1	.091	.029	1
6.35	.579	.827	.038	1	.111	.025	1
7.62	.694	.861	.026	1	.128	.021	1
8.89	.81	.887	.018	1	.145	.019	1
10.16	.926	.904	.017	1	.167	.024	1
12.7	1.157	.94	.016	1	.192	.016	1
15.24	1.389	.975	.016	1			

STATION NO. <u>C11</u> $x = 40.6$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{PU}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{PV}
.064	.005	.035	.128	.581			
.102	.007	.033	.124	.613			
.152	.011	.029	.137	.56			
.203	.015	.029	.138	.562			
.305	.022	.044	.146	.592			
.406	.03	.042	.148	.582			
.508	.037	.056	.155	.596			
.635	.047	.113	.167	.723	0	.055	.494
.762	.056	.116	.169	.738			
1.02	.075	.188	.167	.837			
1.27	.093	.234	.161	.91	.014	.059	.593
1.52	.112	.278	.158	.937			
1.91	.14	.288	.166	.943	.036	.063	.714
2.03	.15	.342	.151	.993			
2.54	.187	.392	.135	1	.052	.061	.788
3.05	.224	.434	.126	1			
3.18	.234	.447	.124	1	.076	.054	.912
3.56	.262	.495	.11	1			
3.81	.28	.502	.103	1	.096	.047	.982
4.06	.299	.512	.107	1			
4.57	.336	.555	.094	1			
5.08	.374	.578	.085	1	.135	.039	1
6.35	.467	.643	.077	1	.164	.032	1
7.62	.561	.709	.058	1	.194	.028	1
8.89	.654	.752	.042	1	.218	.022	1
10.16	.748	.783	.026	1	.241	.02	1
12.7	.935	.815	.016	1	.284	.015	1
15.24	1.12	.834	.014	1	.322	.013	1
17.78	1.31	.85	.014	1	.364	.014	1
20.32	1.5	.862	.014	1	.409		
22.86	1.68	.844	.028	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION (INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER

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STATION NO <u>C13</u> $x = 48.3$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.064	.004	-.039	.0796	.317			
.102	.006	-.064	.0755	.222			
.152	.009	-.07	.0828	.222			
.203	.011	-.059	.0842	.267			
.305	.017	-.06	.0887	.263			
.406	.023	-.07	.0913	.24			
.508	.029	-.054	.0955	.288			
.635	.036	-.075	.0938	.229	-.006	.046	.478
.762	.043	-.059	.0929	.297			
1.02	.057	-.045	.114	.328			
1.27	.072	-.026	.12	.408	-.005	.065	.508
1.52	.086	-.008	.116	.431			
1.91	.108	.008	.141	.48	-.003	.07	.51
2.03	.115	.011	.131	.473			
2.54	.144	.043	.177	.6	.011	.082	.586
3.05	.172	.107	.177	.682			
3.18	.18	.137	.195	.718	.027	.082	.627
3.56	.201	.172	.175	.816			
3.81	.216	.203	.203	.81	.043	.076	.711
4.06	.23	.229	.181	.888			
4.57	.259	.272	.171	.943			
5.08	.287	.331	.18	.949	.077	.075	.82°
6.35	.359	.407	.162	1	.13	.067	.96°
7.62	.431	.5	.124	1	.174	.057	1
8.89	.503	.566	.0941	1	.212	.048	1
10.16	.575	.619	.0798	1	.249	.035	1
12.7	.718	.684	.0508	1	.305	.023	1
15.24	.862	.727	.0246	1	.352	.019	1
17.78	1.01	.742	.018	1	.394	.018	1
20.32	1.15	.75	.0162	1	.435	.015	1
22.86	1.29	.759	.0153	1	.475	.016	1
25.4	1.44	.754			.532		

STATION NO <u>C14</u> $x = 52.1$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.064	.003	-.036	.111	.308			
.102	.005	-.037	.121	.303			
.152	.008	-.047	.107	.269			
.203	.01	-.048	.106	.261			
.305	.016	-.056	.101	.239			
.508	.026	-.065	.097	.242			
.635	.033	-.089	.124	.124	.001	.037	.537
.762	.039	-.082	.086	.177			
1.02	.052	-.079	.093	.211			
1.27	.066	-.082	.086	.208	.003	.052	.543
1.52	.079	-.059	.106	.281			
2.03	.105	-.033	.123	.362			
2.54	.131	-.022	.133	.416	.012	.065	.575
3.05	.157	.035	.15	.549			
3.56	.183	.07	.17	.615			
3.81	.197	.085	.184	.623	.023	.081	.607
4.06	.21	.102	.18	.666			
4.57	.236	.134	.184	.729			
5.08	.262	.19	.199	.8	.045	.078	.726
6.35	.328	.279	.191	.906	.082	.085	.825
7.62	.393	.36	.18	.981	.122	.08	.923
8.89	.459	.45	.148	1	.166	.07	.995
10.16	.524	.509	.116	1	.216	.059	1
12.7	.655	.594	.084	1	.29	.036	1
15.24	.786	.662	.054	1	.347	.026	1
17.78	.917	.691	.029	1	.394	.021	1
20.32	1.05	.695	.022	1	.433	.017	1
22.86	1.18	.694	.018	1	.484	.018	1
25.4	1.31	.694	.016	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C15</u> $x = 55.9$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.003	-.049	.063	.249			
.102	.005	-.071	.063	.143			
.152	.007	-.079	.073	.157			
.203	.009	-.088	.069	.122			
.305	.014	-.095	.064	.084			
.508	.023	-.097	.069	.093			
.635	.029	-.098	.072	.083	0	.03	.502
.762	.034	-.106	.066	.071			
1.02	.046	-.099	.072	.116			
1.27	.057	-.111	.076	.109	.003	.044	.53
1.52	.069	-.1	.086	.149			
1.91	.086	-.094	.09	.173	.006	.05	.558
2.03	.091	-.091	.091	.179			
2.54	.114	-.072	.103	.257	.007	.053	.571
3.05	.137	-.055	.114	.29			
3.18	.143	-.055	.118	.297	.017	.065	.607
3.56	.16	-.025	.128	.375			
3.81	.171	-.012	.127	.44	.023	.07	.641
4.06	.183	.005	.144	.436			
4.57	.20	.019	.142	.492			
5.08	.229	.065	.173	.549	.037	.077	.688
6.35	.286	.164	.194	.769	.059	.081	.766
7.62	.343	.216	.209	.811	.085	.079	.849
8.89	.4	.32	.196	.931	.115	.083	.899
10.16	.457	.372	.17	.994	.149	.086	.944
12.7	.571	.486	.136	1	.229	.071	1
15.24	.686	.569	.085	1	.305	.046	1
17.78	.8	.615	.053	1	.361	.028	1
20.32	.914	.623	.036	1	.404	.022	1
22.86	1.03	.608	.024	1	.446	.019	1

STATION NO <u>C16</u> $x = 59.7$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.003	-.066	.055	.122			
.102	.004	-.079	.059	.116			
.152	.006	-.097	.059	.076			
.203	.008	-.097	.063	.07			
.305	.012	-.107	.06	.045			
.508	.02	-.11	.064	.041			
.762	.031	-.117	.061	.031			
1.02	.041	-.119	.062	.036			
1.52	.061	-.126	.059	.019			
1.91	.077	-.104	.082	.139	.012	.045	.612
2.03	.082	-.117	.073	.071			
2.54	.102	-.093	.089	.155	.016	.053	.606
3.05	.122	-.088	.084	.18			
3.18	.128	-.057	.1	.246	.022	.056	.661
3.56	.143	-.091	.084	.14			
3.81	.153	-.045	.112	.292	.029	.06	.647
4.06	.163	-.051	.107	.305			
4.57	.184	-.049	.106	.305			
5.08	.204	.013	.138	.469	.048	.077	.726
6.35	.255	.081	.168	.642	.05	.077	.74
7.62	.306	.143	.177	.752	.068	.084	.761
8.89	.357	.192	.19	.802	.098	.087	.86
10.16	.408	.28	.17	.934	.121	.09	.898
12.7	.51	.359	.171	.977	.17	.083	.978
15.24	.612	.445	.141	1	.236	.076	1
17.78	.714	.538	.105	1	.3	.048	1
20.32	.816	.569	.067	1	.345	.035	1
22.86	.918	.558	.049	1	.376	.034	1
25.4	1.02	.525	.036	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

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STATION NO <u>C18</u> $x = 67.3$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.064	.002	-.125	.058	.008			
.102	.003	-.132	.061	.002			
.152	.005	-.139	.063	0			
.203	.007	-.144	.061	0			
.305	.01	-.146	.059	0			
.508	.016	-.153	.062	0			
.635	.02	-.151	.047	0	-.005	.031	.538
.762	.024	-.151	.058	0			
1.02	.033	-.151	.058	0			
1.27	.041	-.154	.051	0	.008	.036	.571
1.52	.049	-.14	.063	.004			
1.91	.061	-.146	.057	0	.008	.04	.573
2.03	.065	-.144	.059	0			
2.34	.082	-.135	.059	.007	.01	.045	.586
3.05	.098	-.119	.063	.039			
3.18	.102	-.125	.066	.027	.014	.053	.596
3.56	.114	-.114	.065	.049			
3.81	.122	-.109	.051	.08	.012	.061	.579
4.06	.131	-.097	.072	.113			
4.57	.147	-.089	.071	.11			
5.08	.163	-.078	.059	.156	.022	.068	.607
6.35	.204	-.056	.069	.263	.032	.077	.637
7.62	.245	-.017	.078	.408	.036	.09	.676
8.89	.285	.014	.097	.494	.051	.099	.772
10.16	.326	.07	.118	.599	.065	.112	.712
12.7	.408	.189	.139	.823	.094	.126	.771
15.24	.489	.277	.153	.958	.132	.123	.866
17.78	.571	.366	.146	.964	.155	.113	.916
20.32	.653	.439	.131	1	.164	.083	.968
22.86	.734	.525	.09	1	.217	.059	1
25.4	.816	.544	.046	1	.203	.023	1
27.94	.897	.527	.032	1	.199	.019	1
30.48	.979	.502	.026	1	.2	.017	
33.02	1.06	.45	.019	1	.181	.014	

STATION NO <u>C20</u> $x = 74.9$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.064	.002	-.127	.06	.004			
.102	.003	-.152	.066	0			
.152	.005	-.169	.067	0			
.203	.006	-.171	.066	0			
.305	.009	-.182	.065	0			
.508	.015	-.188	.065	0			
.635	.019	-.192	.065	0	.001	.032	.521
.762	.023	-.184	.066	0			
1.02	.03	-.175	.067	0			
1.27	.038	-.177	.063	0	.002	.044	.532
1.52	.045	-.165	.063	0			
1.91	.056	-.164	.064	0	-.003	.05	.489
2.03	.06	-.154	.063	0			
2.34	.075	-.146	.063	0	-.001	.056	.509
3.05	.09	-.125	.067	.025			
3.18	.094	-.133	.069	.029	0	.055	.52
3.81	.113	-.119	.067	.049	.003	.057	.535
4.06	.12	-.113	.069	.057			
4.57	.135	-.106	.071	.092			
5.08	.15	-.106	.067	.072	.007	.058	.559
6.35	.188	-.064	.074	.21	.006	.061	.56
7.62	.226	-.054	.08	.257	.011	.063	.578
8.89	.263	-.021	.088	.397	.012	.072	.576
10.16	.301	.015	.101	.547	.012	.072	.582
12.7	.376	.101	.132	.747	.001	.077	.502
15.24	.451	.202	.148	.925	.009	.089	.558
17.78	.527	.286	.154	.987	.003	.096	.53
20.32	.602	.386	.139	1	.006	.093	.526
22.86	.677	.465	.116	1	.013	.09	.59
25.4	.752	.523	.082	1	.027	.068	.704
27.94	.828	.545	.047	1	.034	.04	.801
30.48	.903	.519	.028	1	.028		
33.02	.978	.49	.032	1	.032		

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C22</u> $x = \underline{82.6}$ cm $z = \underline{0}$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.002	-.19	.072	0			
.102	.003	-.188	.073	0			
.152	.005	-.192	.077	0			
.203	.006	-.199	.068	0			
.305	.009	-.199	.07	0			
.508	.016	-.192	.069	0			
.635	.02	-.202	.071	0	-.002	.04	.496
.762	.024	-.191	.071	0			
1.02	.031	-.18	.07	0			
1.27	.039	-.188	.07	0	-.005	.051	.491
1.52	.047	-.161	.073	.005			
1.91	.059	-.158	.073	.004	-.014	.061	.436
2.03	.063	-.147	.071	.006			
2.54	.079	-.131	.071	.037	-.004	.066	.468
3.18	.098	-.125	.072	.051	-.019	.068	.39
3.81	.118	-.123	.076	.068	-.017	.073	.404
4.06	.126	-.103	.076	.106			
4.57	.142	-.093	.079	.147			
5.08	.157	-.098	.079	.121	-.022	.071	.379
6.35	.197	-.042	.082	.228	-.028	.077	.383
7.62	.236	-.031	.083	.374	-.034	.083	.35
8.89	.275	.0034	.086	.519	-.037	.088	.356
10.16	.314	.037	.088	.644	-.046	.089	.335
12.7	.393	.132	.1	.895	-.079	.105	.249
15.24	.472	.23	.108	.995	-.114	.108	.153
17.78	.55	.308	.114	1	-.132	.108	.107
20.32	.629	.399	.109	1	-.151	.108	.088
22.86	.708	.472	.097	1	-.157	.102	.044
25.4	.786	.523	.066	1	-.132	.072	.014
27.94	.865	.545	.039	1	-.133	.051	0
30.48	.943	.524	.027	1	-.087		
33.02	1.02	.503			-.074		

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STATION NO <u>C24</u> $x = \underline{90.2}$ cm $z = \underline{0}$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.002	-.178	.082	.007			
.102	.003	-.18	.083	.012			
.152	.005	-.186	.079	0			
.203	.007	-.189	.077	0			
.305	.01	-.182	.084	.007			
.508	.017	-.167	.079	.005			
.635	.022	-.173	.076	.004	-.014	.054	.418
.762	.026	-.163	.075	.006			
1.02	.035	-.152	.074	.019			
1.27	.043	-.148	.072	.009	-.018	.068	.416
1.52	.052	-.123	.073	.04			
1.91	.065	-.13	.077	.057	-.029	.075	.366
2.03	.069	-.099	.081	.14			
2.54	.087	-.106	.078	.086	-.039	.081	.334
3.05	.104	-.073	.085	.202			
3.18	.108	-.075	.076	.171	-.059	.085	.255
3.56	.121	-.066	.084	.241			
3.81	.13	-.067	.085	.242	-.066	.094	.239
4.06	.139	-.042	.087	.333			
4.57	.156	-.038	.087	.338			
5.08	.173	-.03	.084	.367	-.074	.095	.224
6.35	.217	.0012	.087	.5	-.088	.104	.207
7.62	.26	.034	.087	.657	-.081	.116	.271
8.89	.303	.095	.083	.861	-.12	.107	.136
10.16	.347	.126	.088	.91	-.142	.111	.1
12.7	.433	.217	.087	1	-.185	.11	.036
15.24	.52	.312	.082	1	-.225	.105	.001
17.78	.607	.427	.08	1	-.243	.085	0
20.32	.639	.523	.075	1	-.249	.067	0
22.86	.78	.57	.054	1	-.262	.042	0
25.4	.867	.538	.039	1	-.273	.049	0
27.94	.953	.52	.029	1	-.254	.032	0
30.48	1.04	.496	.022	1	-.239	.015	0

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C26</u> $x = 97.8$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.003	-.089	.086	.17			
.102	.005	-.094	.086	.144			
.152	.008	-.111	.084	.092			
.203	.011	-.104	.088	.12			
.305	.016	-.095	.089	.16			
.508	.027	-.088	.088	.174			
.635	.034	-.078	.077	.181	-.03	.063	.343
.762	.04	-.071	.085	.209			
1.02	.054	-.053	.086	.271			
1.27	.067	-.032	.087	.375	-.048	.079	.275
1.52	.081	-.019	.082	.434			
1.91	.101	-.008	.089	.459	-.082	.093	.22
2.03	.108	-.002	.091	.48			
2.54	.134	.022	.09	.583	-.098	.103	.193
3.05	.161	.041	.09	.647			
3.56	.188	.053	.098	.678			
4.06	.215	.07	.1	.734			
4.57	.242	.097	.097	.833	-.144	.113	
6.35	.336	.134	.094	.915	-.183	.117	.06
7.62	.403	.171	.096	.946	-.202	.112	.035
8.89	.47	.23	.084	1	-.225	.111	.019
10.16	.538	.285	.08	1	-.248	.105	0
12.7	.672	.371	.064	1	-.292	.089	0
15.24	.806	.443	.059	1	-.316	.074	0
17.78	.941	.505	.051	1	-.333	.059	0
20.32	1.08	.546	.042	1	-.346	.043	0
22.86	1.21	.555	.035	1	-.346	.03	0
25.4	1.34	.551	.027	1	-.371	.023	
27.94	1.48	.53	.022	1			

STATION NO <u>C28</u> $x = 105.4$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.064	.003	.067	.097	.768			
.102	.005	.052	.092	.714			
.152	.008	.072	.091	.787			
.203	.01	.089	.096	.824			
.305	.015	.082	.09	.807			
.508	.025	.096	.087	.87			
.635	.032	.111	.095	.865	-.054	.071	.234
.762	.038	.127	.093	.918			
1.02	.051	.136	.091	.931			
1.27	.064	.15	.099	.928	-.086	.081	.152
1.52	.074	.161	.093	.943			
1.91	.095	.16	.1	.943	-.112	.1	.139
2.03	.102	.168	.096	.964			
2.54	.127	.178	.1	.973	-.133	.108	.121
3.05	.153	.219	.098	1			
3.18	.159	.208	.098	.992	-.153	.111	.102
3.56	.178	.245	.097	1			
3.81	.191	.232	.096	1	-.172	.117	.085
4.06	.204	.265	.087	1			
4.57	.229	.271	.099	1			
5.08	.254	.277	.091	1	-.206	.116	.043
6.35	.318	.319	.086	1	-.235	.11	.016
7.62	.382	.37	.073	1	-.244	.109	.006
8.89	.445	.405	.064	1	-.279	.09	0
10.16	.509	.445	.056	1	-.295	.088	0
12.7	.636	.516	.046	1	-.339	.064	0
15.24	.743	.568	.039	1	-.347	.041	0
17.78	.891	.594	.032	1	-.398	.03	0
20.32	1.02	.593	.028	1	-.409	.021	0
22.352	1.12	.592	.025	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C30</u> $x = 113.0$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.044	.004	.261	.093	1			
.102	.006	.281	.099	1			
.152	.009	.294	.095	1			
.203	.012	.31	.095	1			
.305	.019	.32	.093	1			
.508	.031	.333	.092	1			
.635	.039	.347	.087	1	-.059	.065	.202
1.02	.062	.352	.092	1			
1.27	.077	.347	.084	1	-.084	.087	.181
1.52	.093	.384	.084	1			
1.91	.116	.382	.088	1	-.113	.099	.146
2.54	.155	.401	.089	1	-.137	.104	.11
3.05	.185	.41	.085	1			
3.18	.193	.414	.086	1	-.158	.107	.082
3.81	.232	.416	.087	1	-.175	.11	.067
4.06	.247	.441	.083	1			
4.57	.278	.467	.079	1			
5.08	.309	.477	.076	1	-.198	.107	.039
6.35	.386	.494	.075	1	-.225	.101	.011
7.62	.464	.558	.061	1	-.244	.096	0
8.89	.541	.583	.06	1	-.268	.079	0
10.16	.618	.639	.042	1	-.3	.067	0
12.7	.773	.699	.028	1	-.371	.036	0
15.24	.927	.717	.022	1	-.411	.024	0
17.78	1.08	.747	.024	1	-.411		

STATION NO <u>C31</u> $x = 119.4$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{PU}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{PV}
.064	.005	.421	.093	1			
.102	.008	.451	.09	1			
.152	.012	.455	.083	1			
.203	.016	.468	.085	1			
.305	.024	.477	.083	1			
.635	.051	.49	.077	1	-.056	.062	.194
.762	.061	.509	.08	1			
1.02	.081	.512	.08	1			
1.27	.101	.515	.083	1	-.096	.076	.129
1.91	.152	.521	.08	1	-.112	.091	.133
2.03	.162			1			
2.54	.202	.53	.083	1	-.12	.104	.139
3.05	.243			1			
3.18	.253	.539	.092	1	-.145	.103	.094
3.56	.283			1			
3.81	.304	.559	.083	1	-.154	.11	.104
4.06	.324	.596	.083	1			
4.57	.364	.621	.073	1			
6.35	.506	.641	.087	1	-.205	.087	.003
7.62	.607	.719	.075	1	-.212	.076	0
8.89	.709	.786	.031	1	-.255	.054	0
10.16	.81	.822	.025	1	-.274	.042	0
12.7	1.01	.891	.023	1	-.288		
13.97	1.11	.926	.023	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

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STATION NO <u>C34</u> $x = 140.3$ cm $z = 0$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{P_U}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{P_V}
.127	.01	.579	.1				
.203	.016	.614	.103	1			
.305	.024	.643	.102	1			
.406	.032	.659	.1				
.508	.04	.667	.097	1			
.635	.05	.675	.095	1	-.028	.051	.268
.762	.06	.68	.092	1			
1.02	.08	.683	.092	1			
1.27	.1	.689	.089	1	-.035	.059	.277
1.52	.12	.689	.089	1			
1.91	.15			1	-.048	.069	.28
2.03	.16	.691	.089		-.049		
2.54	.2	.692	.093	1	-.053	.081	.253
3.05	.24	.692	.097		-.061		
3.18	.25			1		.081	.231
3.56	.28	.699	.103		-.06		
3.81	.3			1	-.058	.082	.234
4.06	.32	.696	.106		-.058		
4.57	.36	.698	.109		-.058		
5.08	.4	.708	.11	1	-.058	.079	.217
6.35	.5	.722	.107	1	-.057	.044	.171
7.62	.6	.752	.111	1	-.049	.031	.073
8.89	.7	.781	.098	1	-.029	.031	.163
10.16	.8	.809	.085	1	-.02	.027	.217
11.43	.9			1	-.012	.024	.288
12.7	1	.841	.047	1			
13.97	1.1	.847	.042				

STATION NO <u>E6</u> $x = 26.7$ cm $z = -15.24$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{P_U}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{P_V}
.635	.063	.476	.082	1	.003	.036	.517
1.27	.127	.558	.078	1	.014	.038	.631
1.91	.19	.611	.08	1	.02	.036	.697
2.54	.253	.654	.085	1	.041	.036	.869
3.18	.316	.701	.083	1	.049	.033	.931
3.81	.38	.758	.069	1	.059	.03	.985
5.08	.506	.83	.05	1	.076	.025	1
6.35	.633	.896	.024	1	.093	.021	1
7.62	.759	.92	.014	1	.103	.017	1
8.89	.886	.936	.011	1	.113	.013	1
10.16	1.01	.95	.012	1	.121	.012	1
12.7	1.27	.981	.013	1	.134	.013	1
15.24	1.52	1.011	.022	1	.129	.013	1
17.78	1.77	1.013	.038	1	.145	.015	1
20.32	2.03	.973	.052	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>E11</u> $x = 40.6$ cm $z = -15.24$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{P_U}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{P_V}
.064	.005	.053	.103	.688			
.102	.008	.058	.11	.694			
.152	.011	.074	.122	.713			
.203	.015	.077	.125	.699			
.305	.023	.091	.119	.761			
.406	.030	.117	.137	.777			
.508	.038	.119	.137	.801			
.635	.048	.151	.15	.813	.029	.086	.604
.762	.057	.172	.157	.836			
1.02	.076	.236	.148	.925			
1.27	.095	.296	.139	.989	.031	.073	.656
1.52	.114	.304	.137	.992			
1.91	.143	.34	.135	1	.064	.081	.797
2.03	.152	.39	.123	1			
2.54	.191	.442	.103	1	.07	.041	.875
3.05	.229	.445	.111	1			
3.18	.238	.442	.104	1	.089	.053	.958
3.56	.267	.499	.094	1			
3.81	.286	.493	.097	1	.105	.048	.996
4.06	.305	.517	.09	1			
4.57	.343	.547	.086	1			
5.08	.381	.579	.087	1	.14	.04	1
6.35	.476	.638	.075	1	.168	.035	1
7.62	.572	.689	.063	1	.192	.032	1
8.89	.667	.736	.048	1	.215	.029	1
10.16	.762	.771	.035	1	.234	.024	1
12.7	.953	.813	.02	1	.276	.019	1
15.24	1.14	.832	.018	1	.313	.017	1
17.78	1.33	.847	.013	1	.353	.017	1
20.32	1.52	.857	.012	1	.377	.015	1
22.86	1.71	.858	.019	1			

STATION NO <u>E18</u> $x = 47.3$ cm $z = -15.24$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{P_U}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{P_V}
.635	.022	-.142	.061	0	.007	.028	.606
1.27	.044	-.135	.063	.014	.014	.039	.651
1.91	.065	-.128	.068	.031	.014	.042	.646
2.54	.087	-.119	.07	.055	.012	.042	.61
3.18	.109	-.094	.069	.096	.019	.053	.636
3.81	.131	-.089	.07	.121	.017	.058	.616
5.08	.174	-.049	.094	.306	.02	.06	.636
6.35	.218	-.032	.097	.371	.03	.064	.664
7.62	.262	.011	.123	.461	.033	.067	.671
8.89	.305	.077	.141	.65	.042	.073	.696
10.16	.349	.138	.173	.749	.048	.073	.715
12.7	.436	.23	.176	.921	.086	.075	.817
15.24	.523	.358	.149	1	.111	.074	.911
17.78	.61	.434	.107	1	.16	.067	.983
20.32	.697	.5	.081	1	.184	.048	1
22.86	.785	.545	.056	1	.21	.032	1
25.4	.872	.548	.028	1	.211	.024	1
27.94	.959	.524	.023	1	.201	.018	1
30.48	1.05	.488	.02	1	.185	.015	1

STATION NO <u>E31</u> $x = 119.4$ cm $z = -15.24$ cm							
y (cm)	y/δ	U/U_{rel}	$\sqrt{u^2}/U_{rel}$	γ_{P_U}	V/U_{rel}	$\sqrt{v^2}/U_{rel}$	γ_{P_V}
.635	.051	.486	.07	1	-.046	.06	.25
1.27	.101	.517	.071	1	-.082	.075	.15
1.91	.152	.533	.078	1	-.118	.078	.084
2.54	.202	.561	.078	1	-.142	.084	.058
3.18	.253	.581	.075	1	-.163	.079	.015
3.81	.304	.609	.072	1	-.178	.081	.01
5.08	.405	.662	.064	1	-.205	.07	0
6.35	.506	.714	.051	1	-.224	.063	0
7.62	.607	.744	.035	1	-.235	.053	0
8.89	.709	.803	.027	1	-.247	.043	0
10.16	.81	.838	.024	1	-.26	.036	0
11.43	.911	.858					
12.7	1.01	.899					
13.97	1.11	.93					
15.24	1.22	.956					

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

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STATION NO <u>W6</u> $x = 26.7$ cm $z = 15.24$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.635	.063	.462	.084	1	.008	.038	.578
1.27	.127	.545	.075	1	.019	.038	.671
1.91	.19	.603	.076	1	.028	.037	.755
2.54	.253	.656	.079	1	.036	.036	.834
3.18	.316	.716	.074	1	.046	.034	.914
3.81	.38	.743	.073	1	.054	.029	.975
5.08	.506	.829	.047	1	.083	.025	1
6.35	.633	.872	.034	1	.096	.019	1
7.62	.759	.892	.025	1	.109	.016	1
8.89	.886	.929	.015	1	.121	.014	1
10.16	1.01	.953	.011	1	.126	.014	1
12.7	1.27	.977	.014	1	.122	.012	1
15.24	1.52	1.018	.015	1	.132	.014	1
17.78	1.77	1.023	.036	1			
20.32	2.03	.967	.052	1			

STATION NO <u>W11</u> $x = 40.6$ cm $z = 15.24$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{P_U}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{P_V}
.644	.004	.012	.101	.532			
.102	.007	.005	.107	.515			
.152	.011	.009	.109	.473			
.203	.151	.031	.127	.563			
.305	.023	.034	.127	.433			
.406	.03	.011	.119	.477			
.508	.038	.017	.129	.544			
.635	.047	.044	.14	.652	.095	.13	.757
.762	.056	.089	.14	.724			
1.02	.075	.116	.153	.762			
1.27	.094	.161	.162	.824	.083	.113	.77
1.52	.113	.227	.155	.907			
1.91	.141	.255	.16	.931	.107	.109	.865
2.03	.151	.269	.163	.937			
2.54	.188	.336	.14	1	.075	.07	.868
3.05	.226	.349	.148	1			
3.18	.235	.403	.123	1	.095	.061	.945
3.56	.264			1			
3.81	.282	.458	.103	1	.114	.055	.989
4.06	.301			1			
4.57	.339			1			
5.08	.377	.592	.0827	1	.152	.047	1
6.35	.471	.656	.0704	1	.179	.037	1
7.62	.565	.701	.059	1	.208	.033	1
8.89	.659	.741	.046	1	.232	.027	1
10.16	.753			1			1
12.7	.942	.791	.0254	1	.295	.019	1
15.24	1.13	.821	.0239	1	.333	.017	1
17.78	1.32	.84	.0161	1			
20.32	1.51	.85	.0169	1			
22.86	1.7	.813	.0366	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>W18</u> $x = \underline{67.3}$ cm $z = \underline{15.24}$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{PU}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{PV}
.635	.019	-.151	.059	0	.004	.03	.568
1.27	.039	-.152	.056	0	.005	.034	.569
1.91	.058	-.14	.055	0	.008	.038	.58
2.54	.078	-.133	.056	0	.009	.04	.608
3.18	.097	-.111	.04	.033	.008	.047	.56
3.81	.116	-.105	.045	.058	.015	.049	.633
5.08	.155	-.076	.068	.139	.021	.05	.677
6.35	.194	-.053	.081	.263	.025	.056	.688
7.62	.233	-.016	.101	.401	.034	.059	.713
8.89	.272	.023	.117	.529	.044	.067	.727
10.16	.311	.042	.145	.603	.047	.074	.743
12.7	.388	.162	.162	.819	.078	.081	.81
15.24	.466	.283	.175	.939	.116	.083	.896
17.78	.543	.384	.147	1	.137	.075	.958
20.32	.621	.475	.105	1	.167	.072	.989
22.86	.699	.512	.08	1	.197	.051	1
25.4	.776	.529	.049	1	.2	.032	1
27.94	.854	.515	.033	1			
30.48	.932						

STATION NO <u>W31</u> $x = \underline{119.4}$ cm $z = \underline{15.24}$ cm							
y (cm)	y/δ	U/U_{ref}	$\sqrt{u^2}/U_{ref}$	γ_{PU}	V/U_{ref}	$\sqrt{v^2}/U_{ref}$	γ_{PV}
.635	.049	.514		1	.049	.059	.226
1.27	.097	.54		1	.086	.075	.153
1.91	.146	.557		1	.128	.084	.078
2.54	.195	.566		1	.158	.093	.059
3.18	.243	.585		1	.182	.095	.045
3.81	.292	.602		1	.196	.091	.02
5.08	.389	.634	.076	1	.228	.083	0
6.35	.486	.69	.062	1	.248	.069	0
7.62	.584	.743	.039	1	.269	.058	0
8.89	.681	.784	.03	1	.281	.046	0
10.16	.778	.818	.027	1	.294	.036	0
12.7	.973	.892	.023	1			
15.24	1.07	.925	.022	1			

TABLE II MEAN VELOCITY, TURBULENCE, AND FLOW FRACTION
(INTERMITTENCY) DATA MEASURED WITH LASER VELOCIMETER (CONCLUDED)

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STATION NO. <u>C6</u> $x = \underline{26.7}$ cm $z = \underline{0}$ cm											
y,cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.063	0.496	1.000	0.081	0.004	0.535	0.039	-0.0990	0.0145	-0.1031	0.0145
1.270	0.127	0.567	1.000	0.083	0.013	0.625	0.036	-0.1050	0.0125	-0.1175	0.0126
1.905	0.190	0.629	1.000	0.084	0.022	0.718	0.036	-0.0680	0.0099	-0.0876	0.0101
2.540	0.253	0.686	1.000	0.087	0.030	0.815	0.033	-0.0720	0.0008	-0.1017	0.0030
3.175	0.316	0.750	1.000	0.076	0.040	0.904	0.030	-0.0390	0.0051	-0.0390	0.0051
3.810	0.380	0.800	1.000	0.058	0.058	0.990	0.028	-0.0250	0.0040	-0.0432	0.0044
5.080	0.506	0.872	1.000	0.031	0.072	0.990	0.019	-0.0070	0.0036	-0.0118	0.0036
6.350	0.633	0.901	1.000	0.022	0.082	0.990	0.012	-0.0170	0.0013	-0.0198	0.0014
7.620	0.759	0.919	1.000	0.014	0.096	0.990	0.010	-0.0030	0.0009	-0.0039	0.0009
8.890	0.886	0.931	1.000	0.013	0.100	0.990	0.009	-0.0040	0.0010	-0.0068	0.0010
10.160	1.013	0.944	1.000	0.012	0.109	0.990	0.010	-0.0010	0.0012	-0.0015	0.0012
12.700	1.266	0.979	1.000	0.013	0.122	0.990	0.011	-0.0090	0.0012	-0.0093	0.0012
15.240	1.519	1.016	1.000	0.015	0.134	0.990	0.014	-0.0100	0.0013	-0.0100	0.0013
17.780	1.772	1.026	1.000	0.035				-0.0020	0.0027	-0.0020	0.0027

STATION NO. <u>C8</u> $x = \underline{31.8}$ cm $z = \underline{0}$ cm											
y,cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.058	0.401	1.000	0.103	0.008	0.557	0.044	-0.0890	0.0226	-0.1064	0.0226
1.270	0.116	0.487	1.000	0.090	0.024	0.692	0.044	-0.0460	0.0183	-0.0759	0.0184
1.905	0.174	0.556	1.000	0.090	0.039	0.826	0.042	-0.0300	0.0126	-0.0739	0.0133
2.540	0.231	0.613	1.000	0.091				-0.0350	0.0099	-0.1127	0.0118
3.175	0.289	0.651	1.000	0.085	0.059	0.958	0.036	-0.0770	0.0073	-0.1295	0.0089
3.810	0.347	0.705	1.000	0.079	0.069	0.978	0.034	-0.0550	0.0079	-0.1037	0.0092
5.080	0.463	0.783	1.000	0.052	0.091	1.000	0.029	-0.0100	0.0048	-0.0313	0.0053
6.350	0.579	0.827	1.000	0.038	0.111	1.000	0.025	-0.0200	0.0031	-0.0302	0.0033
7.620	0.694	0.861	1.000	0.026	0.128	1.000	0.021	-0.0130	0.0014	-0.0159	0.0016
8.890	0.810	0.887	1.000	0.018	0.145	1.000	0.019	-0.0110	0.0013	-0.0098	0.0013
10.160	0.926	0.904	1.000	0.017	0.167	1.000	0.024	-0.0100	0.0012	-0.0041	0.0014
12.700	1.157	0.940	1.000	0.016	0.192	1.000	0.016	-0.0070	0.0011	-0.0064	0.0011
15.240	1.389	0.975	1.000	0.016				-0.0090	0.0012	-0.0090	0.0012

STATION NO. <u>C11</u> $x = \underline{40.6}$ cm $z = \underline{0}$ cm											
y,cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.047	0.113	0.723	0.167	0.000	0.494	0.055	-0.1130	0.0271	-0.1364	0.0272
1.270	0.093	0.234	0.910	0.161	0.014	0.593	0.059	-0.0160	0.0399	-0.1585	0.0428
2.540	0.187	0.392	1.000	0.135	0.052	0.788	0.061	-0.0110	0.0443	-0.2003	0.0468
3.175	0.234	0.447	1.000	0.124	0.076	0.912	0.054	-0.0490	0.0295	-0.1599	0.0346
3.810	0.280	0.502	1.000	0.103	0.096	0.982	0.047	-0.0300	0.0251	-0.1274	0.0282
5.080	0.374	0.578	1.000	0.085	0.135	1.000	0.039	-0.0040	0.0157	-0.1295	0.0189
6.350	0.467	0.643	1.000	0.077	0.164	1.000	0.032	-0.0140	0.0113	-0.1056	0.0151
7.620	0.561	0.709	1.000	0.058	0.194	1.000	0.028	-0.0500	0.0063	-0.0225	0.0090
8.890	0.654	0.752	1.000	0.042	0.218	1.000	0.022	-0.0120	0.0041	-0.0444	0.0049
10.160	0.748	0.783	1.000	0.026	0.241	1.000	0.020	-0.0110	0.0022	-0.0169	0.0023
12.700	0.935	0.815	1.000	0.014	0.284	1.000	0.015	-0.0020	0.0014	-0.0025	0.0013
15.240	1.121	0.834	1.000	0.014	0.322	1.000	0.013	-0.0070	0.0013	-0.0061	0.0011
17.780	1.308	0.850	1.000	0.014	0.364	1.000	0.014	-0.0010	0.0014	-0.0007	0.0012
20.320	1.495	0.862	1.000	0.014	0.409			-0.0030	0.0008	-0.0030	0.0008

TABLE III REYNOLDS STRESS DATA MEASURED WITH LASER VELOCIMETER

STATION NO. <u>C13</u> $x = 11.3$ cm $z = 0$ cm											
y, cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.036	-0.075	0.229	0.094	-0.006	0.478	0.046	0.0100	0.0151	-0.0418	0.0159
1.270	0.072	-0.026	0.408	0.120	-0.005	0.508	0.065	-0.0190	0.0217	-0.1929	0.0279
1.905	0.108	0.008	0.480	0.141	-0.003	0.510	0.070	0.0160	0.0291	-0.7068	0.0652
2.540	0.144	0.063	0.600	0.177	0.011	0.586	0.082	-0.0930	0.0394	-0.5113	0.0564
3.175	0.180	0.137	0.718	0.195	0.027	0.627	0.082	-0.0780	0.0472	-0.4557	0.0714
3.810	0.216	0.203	0.810	0.203	0.043	0.711	0.076	-0.0650	0.0435	-0.7815	0.0784
5.080	0.287	0.331	0.949	0.180	0.077	0.829	0.075	-0.0650	0.0376	-0.6527	0.0660
6.350	0.359	0.407	1.000	0.162	0.130	0.966	0.067	0.0010	0.0325	-0.6305	0.0652
7.620	0.431	0.500	1.000	0.124	0.174	1.000	0.057	0.1560	0.0271	-0.2542	0.0446
8.890	0.503	0.566	1.000	0.094	0.212	1.000	0.048	0.1000	0.0282	-0.1403	0.0319
10.160	0.575	0.619	1.000	0.080	0.249	1.000	0.035	0.0980	0.0192	-0.1077	0.0234
12.700	0.718	0.684	1.000	0.051	0.305	1.000	0.023	-0.0080	0.0056	-0.0818	0.0079
15.240	0.862	0.727	1.000	0.025	0.352	1.000	0.019	-0.0040	0.0016	-0.0121	0.0020
17.780	1.006	0.742	1.000	0.018	0.394	1.000	0.018	-0.0040	0.0011	-0.0022	0.0013
20.320	1.149	0.750	1.000	0.016	0.435	1.000	0.015	0.0030	0.0010	-0.0001	0.0011
22.860	1.293	0.759	1.000	0.015	0.475	1.000	0.016	-0.0030	0.0009	-0.0003	0.0011
25.400	1.437	0.754			0.532			0.0000	0.0008	0.0000	0.0008

STATION NO. <u>C15</u> $x = 35.9$ cm $z = 0$ cm											
y, cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.029	-0.098	0.083	0.072	0.000	0.502	0.030	0.0340	0.0079	0.0350	0.0079
1.270	0.057	-0.111	0.109	0.076	0.003	0.530	0.044	0.0070	0.0100	0.0163	0.0101
1.905	0.084	-0.094	0.173	0.090	0.006	0.558	0.050	-0.0380	0.0136	-0.0013	0.0141
2.540	0.114	-0.072	0.257	0.103	0.007	0.571	0.053	-0.0780	0.0174	0.0000	0.0190
3.175	0.143	-0.055	0.297	0.118	0.017	0.607	0.065	0.0040	0.0229	0.2808	0.0355
3.810	0.171	-0.012	0.440	0.127	0.023	0.641	0.070	-0.0330	0.0212	0.4893	0.0780
5.080	0.229	0.065	0.569	0.173	0.037	0.688	0.077	0.0220	0.0320	-0.9950	0.0933
6.350	0.286	0.164	0.769	0.194	0.059	0.766	0.081	0.0450	0.0430	-0.9442	0.0985
7.620	0.343	0.216	0.811	0.209	0.085	0.849	0.079	0.1810	0.0450	-1.1401	0.1230
8.890	0.400	0.320	0.931	0.196	0.115	0.899	0.083	0.2710	0.0649	-0.7918	0.1109
10.160	0.457	0.372	0.994	0.170	0.149	0.944	0.086	0.2730	0.0600	-0.5466	0.0912
12.700	0.571	0.486	1.000	0.136	0.229	1.000	0.071	0.2460	0.0428	-0.3632	0.0646
15.240	0.686	0.569	1.000	0.085	0.305	1.000	0.046	0.2390	0.0348	-0.0808	0.0356
17.780	0.800	0.615	1.000	0.053	0.361	1.000	0.028	0.0870	0.0105	-0.0460	0.0132
20.320	0.914	0.623	1.000	0.036	0.404	1.000	0.022	0.0070	0.0036	-0.0343	0.0046
22.860	1.029	0.608	1.000	0.024	0.446	1.000	0.019	0.0100	0.0028	-0.0073	0.0025

STATION NO. <u>C18</u> $x = 67.3$ cm $z = 0$ cm											
y, cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.020	-0.151	0.000	0.047	-0.005	0.538	0.031	-0.0060	0.0069	-0.0041	0.0069
1.270	0.041	-0.154	0.000	0.051	0.008	0.571	0.036	-0.0290	0.0071	-0.0244	0.0072
1.905	0.061	-0.146	0.000	0.057	0.008	0.573	0.040	-0.0570	0.0087	-0.0494	0.0087
2.540	0.082	-0.135	0.007	0.059	0.010	0.586	0.045	-0.0500	0.0095	-0.0390	0.0096
3.175	0.102	-0.125	0.027	0.066	0.014	0.594	0.053	-0.0820	0.0101	-0.0635	0.0105
3.810	0.122	-0.109	0.080	0.051	0.012	0.579	0.061	-0.0620	0.0073	-0.0725	0.0077
5.080	0.163	-0.078	0.156	0.059	0.022	0.607	0.068	-0.0820	0.0093	-0.0968	0.0108
6.350	0.204	-0.056	0.263	0.069	0.032	0.637	0.077	-0.0550	0.0123	-0.0802	0.0189
7.620	0.245	-0.017	0.408	0.078	0.036	0.676	0.090	-0.1270	0.0161	0.0009	0.0498
8.890	0.285	0.014	0.494	0.097	0.051	0.772	0.099	-0.0210	0.0293	0.0281	0.0334
10.160	0.326	0.070	0.599	0.118	0.065	0.712	0.112	0.0660	0.0404	-0.0541	0.0582
12.700	0.408	0.189	0.823	0.139	0.094	0.771	0.126	0.1680	0.0539	0.0185	0.0657
15.240	0.489	0.277	0.958	0.153	0.132	0.866	0.123	0.4180	0.0850	0.0618	0.0895
17.780	0.571	0.366	0.964	0.146	0.155	0.916	0.113	0.4280	0.0759	0.0744	0.0806
20.320	0.653	0.439	1.000	0.131	0.164	0.968	0.083	0.5040	0.0560	0.0494	0.0656
22.860	0.734	0.525	1.000	0.090	0.217	1.000	0.059	0.2280	0.0268	0.0175	0.0311
25.400	0.816	0.544	1.000	0.046	0.203	1.000	0.023	0.0790	0.0048	0.0076	0.0077
27.940	0.897	0.527	1.000	0.032	0.199	1.000	0.019	0.0330	0.0023	0.0028	0.0036
30.480	0.979	0.502	1.000	0.026	0.200		0.017	0.0190	0.0016	0.0006	0.0024

TABLE III REYNOLDS STRESS DATA MEASURED WITH LASER VELOCIMETER (CONT.)

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STATION NO <u>C20</u> $x = 74.9$ cm $z = 0$ cm											
y, cm	y/δ	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U_{ref}^2 x10 ²	\overline{Suv}/U_{ref}^2 x10 ²	$\overline{a\beta}/U_{ref}^2$ x10 ²	$\overline{Sa\beta}/U_{ref}^2$ x10 ²
0.635	0.019	-0.192	0.000	0.065	0.001	0.521	0.032	-0.0330	0.0081	-0.0308	0.0081
1.270	0.038	-0.177	0.000	0.063	0.002	0.532	0.044	-0.0590	0.0097	-0.0567	0.0097
1.905	0.056	-0.164	0.000	0.064	-0.003	0.489	0.050	-0.0550	0.0100	-0.0576	0.0100
2.540	0.075	-0.146	0.000	0.063	-0.001	0.509	0.056	-0.1150	0.0120	-0.1156	0.0120
3.175	0.094	-0.133	0.029	0.069	0.000	0.520	0.055	-0.1010	0.0119	-0.1013	0.0119
3.810	0.113	-0.119	0.049	0.067	0.003	0.535	0.057	-0.0980	0.0125	-0.0947	0.0125
5.080	0.150	-0.106	0.072	0.067	0.007	0.559	0.058	-0.1360	0.0140	-0.1270	0.0141
6.350	0.188	-0.064	0.210	0.074	0.006	0.560	0.061	-0.1240	0.0145	-0.1057	0.0148
7.620	0.226	-0.054	0.257	0.080	0.011	0.578	0.063	-0.1890	0.0188	-0.1256	0.0201
8.890	0.263	-0.021	0.397	0.088	0.012	0.576	0.072	-0.1970	0.0208	-0.0116	0.0319
12.160	0.301	0.015	0.547	0.101	0.012	0.582	0.072	-0.2180	0.0237	-0.2917	0.0386
15.700	0.376	0.101	0.747	0.132	0.001	0.502	0.077	-0.0950	-0.0338	-0.4112	0.0462
15.240	0.451	0.202	0.925	0.148	0.009	0.558	0.089	-0.0730	0.0366	-0.3134	0.0449
17.780	0.527	0.286	0.987	0.154	0.003	0.530	0.096	0.2190	0.0311	0.0675	0.0358
22.320	0.602	0.386	1.000	0.139	0.006	0.526	0.093	0.2880	0.0221	0.2355	0.0231
22.860	0.677	0.465	1.000	0.116	0.013	0.590	0.090	0.1330	0.0092	0.1032	0.0108
25.400	0.752	0.523	1.000	0.082	0.027	0.704	0.068	-0.0260	0.0034	-0.0365	0.0045
27.940	0.828	0.545	1.000	0.047	0.034	0.801	0.040	-0.0040	0.0020	-0.0078	0.0022
30.480	0.903	0.519	1.000	0.028	0.028			-0.0130	0.0017	-0.0130	0.0017
33.020	0.978	0.490	1.000	0.032	0.032			-0.0090	0.0010	-0.0090	0.0010

STATION NO <u>C22</u> $x = 74.9$ cm $z = 0$ cm											
y, cm	y/δ	U/U _{ref}	γ_{PU}	$\sqrt{u^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{v^2}/U_{ref}$	\overline{uv}/U_{ref}^2 x10 ²	\overline{Suv}/U_{ref}^2 x10 ²	$\overline{a\beta}/U_{ref}^2$ x10 ²	$\overline{Sa\beta}/U_{ref}^2$ x10 ²
0.635	0.020	-0.202	0.000	0.071	-0.002	0.496	0.040	-0.0610	0.0113	-0.0639	0.0113
1.270	0.039	-0.188	0.000	0.070	-0.005	0.491	0.051	-0.0970	0.0124	-0.1025	0.0124
1.905	0.059	-0.158	0.004	0.073	-0.014	0.436	0.061	-0.1070	0.0142	-0.1193	0.0145
2.540	0.079	-0.131	0.037	0.071	-0.004	0.468	0.066	-0.1410	0.0158	-0.1423	0.0158
3.175	0.098	-0.125	0.051	0.072	-0.019	0.390	0.068	-0.1830	0.0168	-0.1832	0.0173
3.810	0.118	-0.123	0.068	0.074	-0.017	0.404	0.073	-0.1690	0.0171	-0.1686	0.0178
5.080	0.157	-0.098	0.121	0.079	-0.022	0.379	0.071	-0.1980	0.0190	-0.2046	0.0202
6.350	0.197	-0.062	0.228	0.082	-0.028	0.383	0.077	-0.1990	0.0193	-0.1618	0.0254
7.620	0.236	-0.031	0.374	0.083	-0.034	0.350	0.083	-0.2580	0.0219	0.0205	0.0460
8.890	0.275	0.003	0.519	0.086	-0.037	0.356	0.088	-0.3830	0.0279	0.3736	0.1212
10.160	0.314	0.037	0.644	0.088	-0.046	0.335	0.089	-0.3540	0.0280	0.0643	0.0634
12.700	0.393	0.132	0.895	0.100	-0.079	0.249	0.105	-0.4030	0.0336	-0.2368	0.0501
15.240	0.472	0.230	0.995	0.108	-0.114	0.153	0.108	-0.2050	0.0249	-0.1241	0.0447
17.780	0.550	0.308	1.000	0.114	-0.132	0.107	0.108	0.1260	0.0238	0.1351	0.0427
20.320	0.629	0.399	1.000	0.109	-0.151	0.088	0.108	0.2620	0.0198	0.2036	0.0384
22.860	0.708	0.472	1.000	0.097	-0.157	0.044	0.102	0.1210	0.0106	0.0671	0.0279
25.400	0.786	0.523	1.000	0.066	-0.132	0.014	0.072	0.0070	0.0045	-0.0135	0.0108
27.940	0.865	0.545	1.000	0.039	-0.133	0.000	0.051	0.0020	0.0024	-0.0230	0.0050
30.480	0.943	0.524	1.000	0.027	-0.087			-0.0120	0.0020	0.0003	0.0021
33.020	1.022	0.503			-0.074			-0.0020	0.0012	-0.0019	0.0012

TABLE III REYNOLDS STRESS DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C24</u> x = <u>90.2</u> cm z = <u>0</u> cm											
y,cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{U^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{V^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.022	-0.173	0.004	0.076	-0.014	0.418	0.054	-0.0530	0.0147	-0.0749	0.0149
1.270	0.043	-0.148	0.009	0.072	-0.018	0.416	0.068	-0.1150	0.0173	-0.1184	0.0174
1.905	0.065	-0.130	0.057	0.077	-0.029	0.366	0.075	-0.1900	0.0198	-0.1781	0.0210
2.540	0.087	-0.106	0.086	0.078	-0.039	0.334	0.081	-0.1720	0.0225	-0.1163	0.0255
3.175	0.108	-0.075	0.171	0.076	-0.059	0.255	0.085	-0.3030	0.0264	0.0005	0.0420
3.810	0.130	-0.067	0.242	0.085	-0.064	0.239	0.094	-0.3500	0.0283	0.0735	0.0557
5.080	0.173	-0.030	0.367	0.084	-0.074	0.224	0.095	-0.4250	0.0326	0.3727	0.0772
6.350	0.217	0.001	0.500	0.087	-0.088	0.207	0.104	-0.5510	0.0386	0.5462	1.5843
7.620	0.260	0.034	0.657	0.087	-0.081	0.271	0.116	-0.5760	0.0399	0.1931	0.1882
8.890	0.303	0.095	0.861	0.083	-0.120	0.136	0.107	-0.4640	0.0495	-0.0715	0.1172
10.160	0.347	0.126	0.910	0.088	-0.142	0.100	0.111	-0.6120	0.0456	-0.1583	0.0993
12.700	0.433	0.217	1.000	0.087	-0.185	0.036	0.110	-0.3440	0.0388	-0.2790	0.0546
15.240	0.520	0.312	1.000	0.082	-0.225	0.001	0.105	-0.1230	0.0192	-0.2430	0.0388
17.780	0.607	0.427	1.000	0.080	-0.243	0.000	0.085	0.0860	0.0241	-0.0031	0.0304
20.320	0.639	0.523	1.000	0.075	-0.249	0.000	0.067	0.1800	0.0187	0.1366	0.0236
22.860	0.780	0.570	1.000	0.054	-0.262	0.000	0.042	0.0850	0.0079	0.0952	0.0102
25.400	0.867	0.538	1.000	0.039	-0.273	0.000	0.049	0.0050	0.0035	-0.0324	0.0077
27.940	0.953	0.520	1.000	0.029	-0.254	0.000	0.032	-0.0170	0.0021	-0.0177	0.0035
30.480	1.040	0.494	1.000	0.022	-0.239	0.000	0.015	-0.0180	0.0017	-0.0010	0.0021

STATION NO <u>C26</u> x = <u>97.8</u> cm z = <u>0</u> cm											
y,cm	y/b	U/U _{ref}	γ_{PU}	$\sqrt{U^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{V^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.034	-0.078	0.181	0.077	-0.030	0.343	0.063	-0.1340	0.0191	-0.1652	0.0205
1.270	0.067	-0.032	0.375	0.087	-0.048	0.275	0.079	-0.2720	0.0246	0.0461	0.0600
1.905	0.101	-0.068	0.459	0.089	-0.082	0.220	0.093	-0.3310	0.0295	0.3317	0.0475
2.540	0.134	0.022	0.583	0.090	-0.098	0.193	0.103	-0.4240	0.0338	0.3802	0.2279
3.175								-0.6350	0.0428	0.5359	0.1501
3.810								-0.7550	0.0494	0.6311	0.1774
5.080								-0.8580	0.0529	0.4700	0.1678
6.350	0.336	0.134	0.915	0.094	-0.183	0.060	0.117	-0.9000	0.0541	0.0418	0.1645
7.620	0.403	0.171	0.946	0.096	-0.202	0.035	0.112	-0.7640	0.0472	-0.0410	0.1242
8.890	0.470	0.230	1.000	0.086	-0.225	0.019	0.111	-0.5960	0.0400	-0.2595	0.0846
10.160	0.538	0.285	1.000	0.080	-0.248	0.000	0.105	-0.4000	0.0333	-0.2848	0.0558
12.700	0.672	0.371	1.000	0.064	-0.292	0.000	0.089	-0.2660	0.0292	-0.2481	0.0348
15.240	0.806	0.443	1.000	0.059	-0.316	0.000	0.074	-0.1000	0.0217	-0.1269	0.0211
17.780	0.941	0.505	1.000	0.051	-0.333	0.000	0.059	-0.0160	0.0205	-0.0467	0.0148
20.320	1.075	0.546	1.000	0.042	-0.346	0.000	0.043	-0.0070	0.0096	-0.0068	0.0083
22.860	1.210	0.555	1.000	0.035	-0.366	0.000	0.030	-0.0390	0.0043	-0.0024	0.0060
25.400	1.344	0.551	1.000	0.027	-0.371	0.000	0.023	-0.0230	0.0024	-0.0230	0.0024

TABLE III REYNOLDS STRESS DATA MEASURED WITH LASER VELOCIMETER (CONT.)

STATION NO <u>C28</u> $x = 185.4$ cm $z = 0$ cm											
y,cm	y/δ	U/U _{ref}	γ_{PU}	$\sqrt{U^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{V^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.032	0.111	0.865	0.095	-0.054	0.234	0.071	-0.2110	0.0221	0.0248	0.0335
1.270	0.064	0.150	0.928	0.099	-0.086	0.152	0.081	-0.4440	0.0330	-0.0852	0.0487
1.905	0.095	0.160	0.943	0.100	-0.112	0.139	0.100	-0.4740	0.0359	-0.1628	0.0580
2.540	0.127	0.178	0.973	0.100	-0.133	0.121	0.108	-0.7280	0.0454	-0.2832	0.0791
3.175	0.159	0.208	0.992	0.098	-0.153	0.102	0.111	-0.7980	0.0489	-0.3679	0.0819
3.810	0.191	0.232	1.000	0.096	-0.172	0.085	0.117	-0.3390	0.0528	-0.3138	0.0564
5.080	0.254	0.277	1.000	0.091	-0.206	0.043	0.116	0.0750	0.0616	-0.2262	0.0521
6.350	0.318	0.319	1.000	0.086	-0.235	0.016	0.110	0.3980	0.0660	-0.1073	0.0421
7.620	0.382	0.370	1.000	0.073	-0.244	0.006	0.109	0.3810	0.0587	-0.1508	0.0589
8.890	0.445	0.405	1.000	0.064	-0.279	0.000	0.090	0.3770	0.0514	-0.0531	0.0485
10.160	0.509	0.445	1.000	0.056	-0.295	0.000	0.088	0.1460	0.0372	-0.1553	0.0335
12.700	0.636	0.516	1.000	0.046	-0.339	0.000	0.064	-0.0180	0.0277	-0.0980	0.0173
15.240	0.763	0.568	1.000	0.039	-0.367	0.000	0.041	0.0250	0.0118	0.0030	0.0083
17.780	0.891	0.594	1.000	0.032	-0.398	0.000	0.030	-0.1290	0.0129	-0.0441	0.0119
20.320	1.018	0.593	1.000	0.028	-0.409	0.000	0.021	-0.1460	0.0117	-0.0368	0.0131

STATION NO <u>C30</u> $x = 113.0$ cm $z = 0$ cm											
y,cm	y/δ	U/U _{ref}	γ_{PU}	$\sqrt{U^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{V^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.039	0.347	1.000	0.087	-0.059	0.202	0.065	-0.2370	0.0253	-0.1682	0.0240
1.270	0.077	0.367	1.000	0.084	-0.084	0.181	0.087	-0.2670	0.0274	-0.2497	0.0285
1.905	0.116	0.382	1.000	0.088	-0.113	0.146	0.099	-0.3690	0.0290	-0.3657	0.0325
2.540	0.155	0.401	1.000	0.089	-0.137	0.110	0.104	-0.5070	0.0353	-0.4890	0.0388
3.175	0.193	0.414	1.000	0.086	-0.158	0.082	0.107	-0.4800	0.0378	-0.4933	0.0407
3.810	0.232	0.416	1.000	0.087	-0.175	0.067	0.110	-0.5780	0.0388	-0.5666	0.0438
5.080	0.309	0.477	1.000	0.076	-0.198	0.039	0.107	-0.5880	0.0378	-0.6064	0.0411
6.350	0.386	0.494	1.000	0.075	-0.225	0.011	0.101	-0.5230	0.0330	-0.5156	0.0376
7.620	0.464	0.558	1.000	0.061	-0.244	0.000	0.096	-0.4900	0.0294	-0.5277	0.0322
8.890	0.541	0.583	1.000	0.060	-0.268	0.000	0.079	-0.2950	0.0195	-0.2922	0.0226
10.160	0.618	0.639	1.000	0.042	-0.300	0.000	0.067	-0.1280	0.0113	-0.1863	0.0137
12.700	0.773	0.699	1.000	0.028	-0.371	0.000	0.036	0.0120	0.0043	-0.0146	0.0049
15.240	0.927	0.717	1.000	0.022	-0.411	0.000	0.024	0.0090	0.0030	0.0006	0.0026

STATION NO <u>C31</u> $x = 119.4$ cm $z = 0$ cm											
y,cm	y/δ	U/U _{ref}	γ_{PU}	$\sqrt{U^2}/U_{ref}$	V/U _{ref}	γ_{PV}	$\sqrt{V^2}/U_{ref}$	\overline{uv}/U^2_{ref} x10 ²	$S^{\overline{uv}}/U^2_{ref}$ x10 ²	$\overline{\alpha\beta}/U^2_{ref}$ x10 ²	$S^{\overline{\alpha\beta}}/U^2_{ref}$ x10 ²
0.635	0.051	0.490	1.000	0.077	-0.056	0.194	0.062	-0.1960	0.0208	-0.1674	0.0210
1.270	0.101	0.515	1.000	0.083	-0.096	0.129	0.076	-0.2600	0.0235	-0.2225	0.0244
1.905	0.152	0.521	1.000	0.080	-0.112	0.133	0.091	-0.3820	0.0285	-0.3870	0.0293
2.540	0.202	0.530	1.000	0.083	-0.120	0.139	0.104	-0.5190	0.0350	-0.5529	0.0359
3.175	0.253	0.539	1.000	0.092	-0.145	0.094	0.103	-0.4760	0.0328	-0.4655	0.0357
3.810	0.304	0.559	1.000	0.083	-0.154	0.104	0.110	-0.5910	0.0371	-0.4411	0.0389
5.080							0.087	-0.5200	0.0309	-0.4519	0.0282
6.350	0.506	0.641	1.000	0.087	-0.205	0.008	0.076	-0.5030	0.0281	-0.4101	0.0321
7.620	0.607	0.713	1.000	0.075	-0.212	0.000	0.054	-0.3300	0.0186	-0.2892	0.0211
8.890	0.709	0.786	1.000	0.031	-0.255	0.000	0.042	-0.1430	0.0125	-0.1732	0.0116
10.160	0.810	0.822	1.000	0.025	-0.274	0.000		-0.0320	0.0035	-0.0597	0.0046
12.700	1.012	0.891	1.000	0.023	-0.288			-0.0110	0.0021	0.0066	0.0022
13.970	1.113	0.926	1.000	0.023					0.0000	0.0000	0.0000

TABLE III REYNOLDS STRESS DATA MEASURED WITH LASER VELOCIMETER (CONCLUDED)

STATION NO. C0 z = -24.1 cm z = 0.0 cm					
$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}}$ = .000					
z, cm	y/d	P/Q _{ref}	$\frac{P - P_w}{\rho Q_{ref}}$	$\frac{P - P_w}{\rho Q_{ref}}$	7p
0	.013	.021			
	.017	.017			
	.025	.017			
	.033	.019			
	.043	.023			
	.050	.023			
	.060	.024			
	.066	.024			
	.083	.026			
	.099	.022			
	.116	.026			
	.132	.024			
	.147	.023			
	.165	.023			
	.182	.022			
	.203	.023			
	.224	.023			
	.249	.023			
	.277	.023			
	.305	.023			
	.336	.023			
	.366	.023			
	.395	.023			
	.427	.023			
	.455	.023			
	.489	.023			
	.522	.023			
	.557	.023			
	.595	.023			
	.635	.023			
	.672	.023			
	.708	.023			
	.744	.023			
	.781	.023			
	.819	.023			
	.857	.023			
	.891	.023			
	.924	.023			
	.957	.023			
	.992	.023			
	1.025	.023			
	1.058	.023			
	1.091	.023			
	1.124	.023			
	1.157	.023			
	1.190	.023			
	1.223	.023			
	1.256	.023			
	1.289	.023			
	1.322	.023			
	1.355	.023			
	1.388	.023			
	1.421	.023			
	1.454	.023			
	1.487	.023			
	1.520	.023			
	1.553	.023			
	1.586	.023			
	1.619	.023			
	1.652	.023			
	1.685	.023			
	1.718	.023			
	1.751	.023			
	1.784	.023			
	1.817	.023			
	1.850	.023			
	1.883	.023			
	1.916	.023			
	1.949	.023			
	1.982	.023			
	2.015	.023			
	2.048	.023			
	2.081	.023			
	2.114	.023			
	2.147	.023			
	2.180	.023			
	2.213	.023			
	2.246	.023			
	2.279	.023			
	2.312	.023			
	2.345	.023			
	2.378	.023			
	2.411	.023			
	2.444	.023			
	2.477	.023			
	2.510	.023			
	2.543	.023			
	2.576	.023			
	2.609	.023			
	2.642	.023			
	2.675	.023			
	2.708	.023			
	2.741	.023			
	2.774	.023			
	2.807	.023			
	2.840	.023			
	2.873	.023			
	2.906	.023			
	2.939	.023			
	2.972	.023			
	3.005	.023			
	3.038	.023			
	3.071	.023			
	3.104	.023			
	3.137	.023			
	3.170	.023			
	3.203	.023			
	3.236	.023			
	3.269	.023			
	3.302	.023			
	3.335	.023			
	3.368	.023			
	3.401	.023			
	3.434	.023			
	3.467	.023			
	3.500	.023			
	3.533	.023			
	3.566	.023			
	3.599	.023			
	3.632	.023			
	3.665	.023			
	3.698	.023			
	3.731	.023			
	3.764	.023			
	3.797	.023			
	3.830	.023			
	3.863	.023			
	3.896	.023			
	3.929	.023			
	3.962	.023			
	3.995	.023			
	4.028	.023			
	4.061	.023			
	4.094	.023			
	4.127	.023			
	4.160	.023			
	4.193	.023			
	4.226	.023			
	4.259	.023			
	4.292	.023			
	4.325	.023			
	4.358	.023			
	4.391	.023			
	4.424	.023			
	4.457	.023			
	4.490	.023			
	4.523	.023			
	4.556	.023			
	4.589	.023			
	4.622	.023			
	4.655	.023			
	4.688	.023			
	4.721	.023			
	4.754	.023			
	4.787	.023			
	4.820	.023			
	4.853	.023			
	4.886	.023			
	4.919	.023			
	4.952	.023			
	4.985	.023			
	5.018	.023			
	5.051	.023			
	5.084	.023			
	5.117	.023			
	5.150	.023			
	5.183	.023			
	5.216	.023			
	5.249	.023			
	5.282	.023			
	5.315	.023			
	5.348	.023			
	5.381	.023			
	5.414	.023			
	5.447	.023			
	5.480	.023			
	5.513	.023			
	5.546	.023			
	5.579	.023			
	5.612	.023			
	5.645	.023			
	5.678	.023			
	5.711	.023			
	5.744	.023			
	5.777	.023			
	5.810	.023			
	5.843	.023			
	5.876	.023			
	5.909	.023			
	5.942	.023			
	5.975	.023			
	6.008	.023			
	6.041	.023			
	6.074	.023			
	6.107	.023			
	6.140	.023			
	6.173	.023			
	6.206	.023			
	6.239	.023			
	6.272	.023			
	6.305	.023			
	6.338	.023			
	6.371	.023			
	6.404	.023			
	6.437	.023			
	6.470	.023			
	6.503	.023			
	6.536	.023			
	6.569	.023			
	6.602	.023			
	6.635	.023			
	6.668	.023			
	6.701	.023			
	6.734	.023			
	6.767	.023			
	6.800	.023			
	6.833	.023			
	6.866	.023			
	6.899	.023			
	6.932	.023			
	6.965	.023			
	6.998	.023			
	7.031	.023			
	7.064	.023			
	7.097	.023			
	7.130	.023			
	7.163	.023			
	7.196	.023			
	7.229	.023			
	7.262	.023			
	7.295	.023			
	7.328	.023			
	7.361	.023			
	7.394	.023			
	7.427	.023			
	7.460	.023			
	7.493	.023			
	7.526	.023			
	7.559	.023			
	7.592	.023			
	7.625	.023			
	7.658	.023			
	7.691	.023			
	7.724	.023			
	7.757	.023			
	7.790	.023			
	7.823	.023			
	7.856	.023			
	7.889	.023			
	7.922	.023			
	7.955	.023			
	7.988	.023			
	8.021	.023			
	8.054	.023			
	8.087	.023			
	8.120	.023			
	8.153	.023			
	8.186	.023			
	8.219	.023			
	8.252	.023			
	8.285	.023			
	8.318	.023			
	8.351	.023			
	8.384	.023			
	8.417	.023			
	8.450	.023			
	8.483	.023			
	8.516	.023			
	8.549	.023			
	8.582	.023			
	8.615	.023			
	8.648	.023			
	8.681	.023			
	8.714	.023			
	8.747	.023			
	8.780	.023			
	8.813	.023			
	8.846	.023			
	8.879	.023			
	8.912	.023			
	8.945	.023			
	8.978	.023			
	9.011	.023			
	9.044	.023			
	9.077	.023			
	9.110	.023			
	9.143	.023			
	9.176	.023			
	9.209	.023			
	9.242	.023			
	9.275	.023			
	9.308	.023			
	9.341	.023			
	9.374	.023			
	9.407	.023			
	9.440	.023			
	9.473	.023			
	9.506	.023			
	9.539	.023			
	9.572	.023			
	9.605	.023			
	9.638	.023			
	9.671	.023			
	9.704	.023			
	9.737	.023			
	9.770	.023			
	9.803	.023			
	9.836	.023			
	9.869	.023			
	9.902	.023			
	9.935	.023			
	9.968	.023			
	10				

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STATION NO. C4	z = 19.1 cm z = 0.0 cm	$\frac{w_w - p_{atm}}{p_{atm}}$		
z, cm	y/d	p/p_{atm}	$\frac{w - p_{atm}}{p_{atm}}$	η_p
0	0	.119		
0.022	.0023	.249		
0.07	.0071	.314		
0.09	.0094	.344		
0.123	.0134	.371		
0.149	.0161	.384		
0.199	.0216	.41		
0.270	.0271	.428		
0.304	.0307	.458		
0.315	.0369	.528		
0.362	.0826	.546		
1.02	1.102	.581		
1.07	1.137	.62		
2.02	2.052	.667		
2.03	2.052	.67		
2.54	2.754	.738		
3.05	3.105	.767		
3.56	3.856	.793		
4.06	4.406	.815		
4.57	4.957	.847		
5.08	5.508	.894		
5.72	6.257	.927		
6.35	6.885	.922		
6.99	7.534	.942		
7.62	8.262	.957		
8.26	8.951	.977		
8.93	9.633	.987		
10.2	1.102	.988		
10.8	1.170	.99		
1.239	1.239	.992		
1.308	1.308	.992		

STATION NO. C5 $z = 24.1 \text{ cm}$ $\sigma = 0.0 \text{ cm}$				
$\frac{p_w - p_{atm}}{p_{atm}} / \frac{Q_{ref}}{Q_{ref}} = .181$				
Y. cm	y/d	P/Q_{ref}	$(p - p_w)/Q_{ref}$	γp
0	0	.0022	.181	
	.047	.0047	.268	
	.083	.0073	.303	
	.119	.0099	.332	
	.155	.0124	.359	
	.191	.0149	.379	.179
	.227	.0175	.404	.196
	.263	.0201	.421	
	.299	.0225	.436	.173
	.335	.0249	.449	.153
	.371	.0274	.461	.133
	.407	.0298	.471	.111
	.443	.0323	.478	.088
	.479	.0347	.483	.064
	.515	.0371	.486	.039
	.551	.0395	.487	.014
	.587	.0419	.486	
	.623	.0443	.483	
	.659	.0467	.478	
	.695	.0491	.471	
	.731	.0515	.461	
	.767	.0539	.448	
	.803	.0563	.432	
	.839	.0587	.413	
	.875	.0611	.392	
	.911	.0635	.368	
	.947	.0659	.341	
	.983	.0683	.312	
	1.019	.0707	.281	
	1.055	.0731	.248	
	1.091	.0755	.213	
	1.127	.0779	.176	
	1.163	.0803	.137	
	1.199	.0827	.097	
	1.235	.0851	.055	
	1.271	.0875	.012	
	1.307	.0899	-.031	
	1.343	.0923	-.073	
	1.379	.0947	-.114	
	1.415	.0971	-.154	
	1.451	.0995	-.194	
	1.487	.1019	-.234	
	1.523	.1043	-.274	
	1.559	.1067	-.314	
	1.595	.1091	-.354	
	1.631	.1115	-.394	
	1.667	.1139	-.434	
	1.703	.1163	-.474	
	1.739	.1187	-.514	
	1.775	.1211	-.554	
	1.811	.1235	-.594	
	1.847	.1259	-.634	
	1.883	.1283	-.674	
	1.919	.1307	-.714	
	1.955	.1331	-.754	
	1.991	.1355	-.794	
	2.027	.1379	-.834	
	2.063	.1403	-.874	
	2.099	.1427	-.914	
	2.135	.1451	-.954	
	2.171	.1475	-.994	
	2.207	.1499	-.1.034	
	2.243	.1523	-.1.074	
	2.279	.1547	-.1.114	
	2.315	.1571	-.1.154	
	2.351	.1595	-.1.194	
	2.387	.1619	-.1.234	
	2.423	.1643	-.1.274	
	2.459	.1667	-.1.314	
	2.495	.1691	-.1.354	
	2.531	.1715	-.1.394	
	2.567	.1739	-.1.434	
	2.603	.1763	-.1.474	
	2.639	.1787	-.1.514	
	2.675	.1811	-.1.554	
	2.711	.1835	-.1.594	
	2.747	.1859	-.1.634	
	2.783	.1883	-.1.674	
	2.819	.1907	-.1.714	
	2.855	.1931	-.1.754	
	2.891	.1955	-.1.794	
	2.927	.1979	-.1.834	
	2.963	.2003	-.1.874	
	3.0	.2027	-.1.914	
	3.036	.2051	-.1.954	
	3.072	.2075	-.1.994	
	3.108	.2099	-.2.034	
	3.144	.2123	-.2.074	
	3.18	.2147	-.2.114	
	3.216	.2171	-.2.154	
	3.252	.2195	-.2.194	
	3.288	.2219	-.2.234	
	3.324	.2243	-.2.274	
	3.36	.2267	-.2.314	
	3.396	.2291	-.2.354	</

STATION NO. C6	z = 26.7 cm z = 0.0 cm			
	$\frac{w_{ref} - w_{ref}}{Q_{ref}} = .222$			
Y, cm	y/d	$\frac{w - w_{ref}}{Q_{ref}}$	γp	
0	0	.222		
.022	0.0022	.29		
.047	.0047	.327		
.072	.0072	.35		
.098	.0098	.37		
.123	.0123	.381		
.149	.0149	.396		
.175	.0175	.41		
.200	.0200	.42		
.227	.0227	.42		
.254	.0254	.47	.213	1
.280	.0280	.497		
.307	.0307	.511		
.333	.0333	.526	.213	1
.360	.0360	.536		
.386	.0386	.549		
.413	.0413	.563		
.439	.0439	.573		
.466	.0466	.589		
.492	.0492	.604		
.519	.0519	.619		
.545	.0545	.633		
.572	.0572	.647		
.598	.0598	.661	.178	
.625	.0625	.675		
.651	.0651	.689		
.678	.0678	.703		
.704	.0704	.717		
.731	.0731	.731		
.757	.0757	.745	.178	
.784	.0784	.759		
.810	.0810	.773		
.837	.0837	.787		
.863	.0863	.801	.178	
.890	.0890	.815		
.916	.0916	.829	.178	
.943	.0943	.843		
.969	.0969	.857	.178	
.996	.0996	.871		
1.022	.1022	.885		
1.048	.1048	.899		
1.075	.1075	.913		
1.101	.1101	.927		
1.128	.1128	.941		
1.154	.1154	.955		
1.181	.1181	.969		
1.207	.1207	.983		
1.234	.1234	.997		
1.260	.1260	1.011		
1.287	.1287	1.025	.067	1
1.313	.1313	1.039		
1.340	.1340	1.053		
1.366	.1366	1.067		
1.393	.1393	1.081		
1.419	.1419	1.095		
1.446	.1446	1.109		
1.472	.1472	1.123		
1.500	.1500	1.137		
1.526	.1526	1.151		
1.553	.1553	1.165		
1.579	.1579	1.179		
1.606	.1606	1.193		
1.632	.1632	1.207		
1.659	.1659	1.221		
1.685	.1685	1.235	.127	
1.712	.1712	1.249		
1.738	.1738	1.263		
1.765	.1765	1.277		
1.791	.1791	1.291		
1.818	.1818	1.305		
1.844	.1844	1.319		
1.871	.1871	1.333		
1.897	.1897	1.347		
1.924	.1924	1.361		
1.950	.1950	1.375		
1.977	.1977	1.389		
2.003	.2003	1.403		
2.030	.2030	1.417		
2.056	.2056	1.431		
2.083	.2083	1.445		
2.109	.2109	1.459		
2.136	.2136	1.473		
2.162	.2162	1.487		
2.189	.2189	1.501		
2.215	.2215	1.515		
2.242	.2242	1.529		
2.268	.2268	1.543		
2.295	.2295	1.557		
2.321	.2321	1.571		
2.348	.2348	1.585		
2.374	.2374	1.599		
2.401	.2401	1.613		
2.427	.2427	1.627		
2.454	.2454	1.641		
2.480	.2480	1.655		
2.507	.2507	1.669		
2.533	.2533	1.683		
2.560	.2560	1.697		
2.586	.2586	1.711		
2.613	.2613	1.725		
2.639	.2639	1.739		
2.666	.2666	1.753		
2.692	.2692	1.767		
2.719	.2719	1.781		
2.745	.2745	1.795		
2.772	.2772	1.809		
2.798	.2798	1.823		
2.825	.2825	1.837		
2.851	.2851	1.851		
2.878	.2878	1.865		
2.904	.2904	1.879		
2.931	.2931	1.893		
2.957	.2957	1.907		
2.984	.2984	1.921		
3.010	.3010	1.935		
3.037	.3037	1.949		
3.063	.3063	1.963		
3.090	.3090	1.977		
3.116	.3116	1.991		
3.143	.3143	2.005		
3.169	.3169	2.019		
3.196	.3196	2.033		
3.222	.3222	2.047		
3.249	.3249	2.061		
3.275	.3275	2.075		
3.302	.3302	2.089		
3.328	.3328	2.103		
3.355	.3355	2.117		
3.381	.3381	2.131		
3.408	.3408	2.145		
3.434	.3434	2.159		
3.461	.3461	2.173		
3.487	.3487	2.187		
3.514	.3514	2.201		
3.540	.3540	2.215		
3.567	.3567	2.229		
3.593	.3593	2.243		
3.620	.3620	2.257		
3.646	.3646	2.271		
3.673	.3673	2.285		
3.699	.3699	2.299		
3.726	.3726	2.313		
3.752	.3752	2.327		
3.779	.3779	2.341		
3.805	.3805	2.355		
3.832	.3832	2.369		
3.858	.3858	2.383		
3.885	.3885	2.397		
3.911	.3911	2.411		
3.938	.3938	2.425		
3.964	.3964	2.439		
3.991	.3991	2.453		
4.017	.4017	2.467		
4.044	.4044	2.481		
4.070	.4070	2.495		
4.097	.4097	2.509		
4.123	.4123	2.523		
4.150	.4150	2.537		
4.176	.4176	2.551		
4.203	.4203	2.565		
4.229	.4229	2.579		
4.256	.4256	2.593		
4.282	.4282	2.607		
4.309	.4309	2.621		
4.335	.4335	2.635		
4.362	.4362	2.649		
4.388	.4388	2.663		
4.415	.4415	2.677		
4.441	.4441	2.691		
4.468	.4468	2.705		
4.494	.4494	2.719		
4.521	.4521	2.733		
4.547	.4547	2.747		
4.574	.4574	2.761		
4.600	.4600	2.775		
4.627	.4627	2.789		
4.653	.4653	2.803		
4.680	.4680	2.817		
4.706	.4706	2.831		
4.733	.4733	2.845		
4.759	.4759	2.859		
4.786	.4786	2.873		
4.812	.4812	2.887		
4.839	.4839	2.901		
4.865	.4865	2.915		
4.892	.4892	2.929		
4.918	.4918	2.943		
4.945	.4945	2.957		
4.971	.4971	2.971		
5.000	.5000	2.985		
5.026	.5026	2.999		
5.053	.5053	3.013		
5.079	.5079	3.027		
5.106	.5106	3.041		
5.132	.5132	3.055		
5.159	.5159	3.069		
5.185	.5185	3.083		
5.212	.5212	3.097		
5.238	.5238	3.111		
5.265	.5265	3.125		
5.291	.5291	3.139		
5.318	.5318	3.153		
5.344	.5344	3.167		
5.371	.5371	3.181		
5.397	.5397	3.195		
5.424	.5424	3.209		
5.450	.5450	3.223		
5.477	.5477	3.237		
5.503	.5503	3.251		
5.530	.5530	3.265		
5.556	.5556	3.279		
5.583	.5583	3.293		
5.609	.5609	3.307		
5.636	.5636	3.321		
5.662	.5662	3.335		
5.689	.5689	3.349		
5.715	.5715	3.363		
5.742	.5742	3.377		
5.768	.5768	3.391		
5.795	.5795	3.405		
5.821	.5821	3.419		
5.848	.5848	3.433		
5.874	.5874	3.447		
5.901	.5901	3.461		
5.927	.5927	3.475		
5.954	.5954	3.489		
5.980	.5980	3.503		
6.007	.6007	3.517		
6.033	.6033	3.531		
6.060	.6060	3.545		
6.086	.6086	3.559		
6.113	.6113	3.573		
6.139	.6139	3.587		
6.166	.6166	3.601		
6.192	.6192	3.615		
6.219	.6219	3.629		
6.245	.6245	3.643		
6.272	.6272	3.657		
6.298	.6298	3.671		
6.325	.6325	3.685		
6.351	.6351	3.699		
6.378	.6378	3.713		
6.404	.6404	3.727		
6.431	.6431	3.741		
6.457	.6457	3.755		
6.484	.6484	3.769		
6.510	.6510	3.783		
6.537	.6537	3.797		
6.563	.6563	3.811		
6.590	.6590	3.825		
6.616	.6616	3.839		
6.643	.6643	3.853		
6.669	.6669	3.867		
6.696	.6696	3.881		
6.722	.6722	3.895		
6.749	.6749	3.909		
6.775	.6775	3.923		
6.802	.6802	3.937		
6.828	.6828	3.951		
6.855	.6855	3.965		
6.881	.6881	3.979		
6.908	.6908	3.993		
6.934	.6934	4.007		
6.961	.6961	4.021		
6.987	.6987	4.035		
7.014	.7014	4.049		
7.040	.7040	4.063		
7.067	.7067	4.077		
7.093	.7093	4.091		
7.120	.7120	4.105		
7.146	.7146	4.119		
7.173	.7173	4.133		
7.199	.7199	4.147		
7.226	.7226	4.161		
7.252	.7252	4.175		
7.279	.7279	4.189		
7.305	.7305	4.203		
7.332	.7332	4.217		
7.358	.7358	4.231		
7.385	.7385	4.245		
7.411	.7411	4.259		
7.438	.7438	4.273		
7.464	.7464	4.287		
7.491	.7491	4.301		
7.517	.7517	4.315		
7.544	.7544	4.329		
7.570	.7570	4.343		
7.597	.7597	4.357		
7.623	.7623	4.371		
7.650	.7650	4.385		
7.676	.7676	4.399		
7.703	.7703	4.413		
7.729	.7729	4.427		
7.756	.7756	4.441		
7.782	.7782	4.455		
7.809	.7809	4.469		
7.835	.7835	4.483		
7.862	.7862	4.497		
7.888	.7888	4.511		
7.915	.7915	4.525		
7.941	.7941	4.539		
7.968	.7968	4.553		
8.000				

STATION NO. C7 $z = 29.2$ $\cos z = 0.0$ $\cos z = 0.0$ $\cos z = 0.0$				
$\frac{p_{\text{atm}} - p_{\text{ref}}}{p_{\text{ref}}} \cdot \frac{10^4 \text{ g/cm}^2}{1}$				
z, cm	y/δ	P/P_{ref}	$(p - p_{\text{ref}})/P_{\text{ref}}$	γP
0	0	265		
0.022	0.0020	321		
0.047	0.0043	333		
0.072	0.0066	36		
0.096	0.0089	37		
0.121	0.0113	38		
0.146	0.0136	39		
0.169	0.0162	393		
0.200	0.0228	409		
0.237	0.0344	439		
0.274	0.0459	457		
0.304	0.0574	463		
0.332	0.0692	503		
0.358	0.0812	554		
0.382	0.0926	588		
0.404	0.1127	1157		
0.424	0.1389	607		
0.442	0.1620	637		
0.458	0.1821	651		
0.472	0.2021	691		
0.484	0.2314	705		
0.494	0.2777	718		
0.504	0.3240	739		
0.512	0.3741	788		
0.518	0.4271	856		
0.522	0.4829	916		
0.526	0.5414	985		
0.528	0.6027	988		
0.529	0.6667	1.001		
0.530	0.7334	8836		
0.531	0.8028	1.004		
0.532	0.8747	1.005		
0.533	0.9497	1.007		
0.534	1.0277	1.004		
0.535	1.1083	1.006		
0.536	1.1913	1.006		
0.537	1.2766	1.009		
0.538	1.3642	1.007		
0.539	1.4540	1.011		
0.540	1.5460	1.004		
0.541	1.6402	995		
0.542	1.7365	995		
0.543	1.8349	995		
0.544	1.9353	995		
0.545	2.0377	995		
0.546	2.1420	995		
0.547	2.2482	995		
0.548	2.3562	995		
0.549	2.4660	995		
0.550	2.5776	995		
0.551	2.6909	995		
0.552	2.8059	995		
0.553	2.9225	995		
0.554	3.0407	995		
0.555	3.1604	995		
0.556	3.2816	995		
0.557	3.4043	995		
0.558	3.5285	995		
0.559	3.6542	995		
0.560	3.7813	995		
0.561	3.9098	995		
0.562	4.0397	995		
0.563	4.1710	995		
0.564	4.3037	995		
0.565	4.4378	995		
0.566	4.5733	995		
0.567	4.7092	995		
0.568	4.8465	995		
0.569	4.9851	995		
0.570	5.1250	995		
0.571	5.2661	995		
0.572	5.4084	995		
0.573	5.5519	995		
0.574	5.6965	995		
0.575	5.8422	995		
0.576	5.9890	995		
0.577	6.1368	995		
0.578	6.2856	995		
0.579	6.4354	995		
0.580	6.5861	995		
0.581	6.7378	995		
0.582	6.8904	995		
0.583	7.0439	995		
0.584	7.1983	995		
0.585	7.3536	995		
0.586	7.5098	995		
0.587	7.6668	995		
0.588	7.8246	995		
0.589	7.9832	995		
0.590	8.1425	995		
0.591	8.3025	995		
0.592	8.4636	995		
0.593	8.6257	995		
0.594	8.7887	995		
0.595	8.9527	995		
0.596	9.1176	995		
0.597	9.2834	995		
0.598	9.4501	995		
0.599	9.6177	995		
0.600	9.7862	995		
0.601	9.9556	995		
0.602	10.1259	995		
0.603	10.2971	995		
0.604	10.4692	995		
0.605	10.6422	995		
0.606	10.8161	995		
0.607	10.9909	995		
0.608	11.1666	995		
0.609	11.3432	995		
0.610	11.5207	995		
0.611	11.6991	995		
0.612	11.8784	995		
0.613	12.0586	995		
0.614	12.2397	995		
0.615	12.4216	995		
0.616	12.6044	995		
0.617	12.7881	995		
0.618	12.9727	995		
0.619	13.1582	995		
0.620	13.3445	995		
0.621	13.5317	995		
0.622	13.7198	995		
0.623	13.9087	995		
0.624	14.0985	995		
0.625	14.2892	995		
0.626	14.4807	995		
0.627	14.6730	995		
0.628	14.8661	995		
0.629	15.0601	995		
0.630	15.2549	995		
0.631	15.4505	995		
0.632	15.6469	995		
0.633	15.8441	995		
0.634	16.0421	995		
0.635	16.2409	995		
0.636	16.4405	995		
0.637	16.6409	995		
0.638	16.8421	995		
0.639	17.0441	995		
0.640	17.2469	995		
0.641	17.4505	995		
0.642	17.6549	995		
0.643	17.8601	995		
0.644	18.0661	995		
0.645	18.2728	995		
0.646	18.4802	995		
0.647	18.6884	995		
0.648	18.8973	995		
0.649	19.1070	995		
0.650	19.3174	995		
0.651	19.5285	995		
0.652	19.7403	995		
0.653	19.9528	995		
0.654	20.1660	995		
0.655	20.3800	995		
0.656	20.5947	995		
0.657	20.8101	995		
0.658	21.0262	995		
0.659	21.2430	995		
0.660	21.4605	995		
0.661	21.6787	995		
0.662	21.8976	995		
0.663	22.1172	995		
0.664	22.3375	995		
0.665	22.5585	995		
0.666	22.7802	995		
0.667	22.9926	995		
0.668	23.2057	995		
0.669	23.4195	995		
0.670	23.6340	995		
0.671	23.8492	995		
0.672	24.0651	995		
0.673	24.2817	995		
0.674	24.4990	995		
0.675	24.7170	995		
0.676	24.9357	995		
0.677	25.1551	995		
0.678	25.3752	995		
0.679	25.5960	995		
0.680	25.8175	995		
0.681	26.0397	995		
0.682	26.2626	995		
0.683	26.4862	995		
0.684	26.7105	995		
0.685	26.9355	995		
0.686	27.1612	995		
0.687	27.3876	995		
0.688	27.6147	995		
0.689	27.8425	995		
0.690	28.0710	995		
0.691	28.3002	995		
0.692	28.5301	995		
0.693	28.7607	995		
0.694	28.9920	995		
0.695	29.2240	995		
0.696	29.4567	995		
0.697	29.6901	995		
0.698	29.9242	995		
0.699	30.1590	995		
0.700	30.3945	995		
0.701	30.6307	995		
0.702	30.8676	995		
0.703	31.1052	995		
0.704	31.3435	995		
0.705	31.5825	995		
0.706	31.8222	995		
0.707	32.0626	995		
0.708	32.3037	995		
0.709	32.5454	995		
0.710	32.7878	995		
0.711	33.0308	995		
0.712	33.2745	995		
0.713	33.5188	995		
0.714	33.7638	995		
0.715	34.0094	995		
0.716	34.2556	995		
0.717	34.5024	995		
0.718	34.7498	995		
0.719	34.9978	995		
0.720	35.2464	995		
0.721	35.4956	995		
0.722	35.7454	995		
0.723	35.9958	995		
0.724	36.2468	995		
0.725	36.4984	995		
0.726	36.7506	995		
0.727	37.0034	995		
0.728	37.2568	995		
0.729	37.5108	995		
0.730	37.7654	995		
0.731	38.0206	995		
0.732	38.2764	995		
0.733	38.5328	995		
0.734	38.7898	995		
0.735	39.0474	995		
0.736	39.3056	995		
0.737	39.5644	995		
0.738	39.8238	995		
0.739	40.0838	995		
0.740	40.3444	995		
0.741	40.6056	995		
0.742	40.8674	995		
0.743	41.1298	995		
0.744	41.3928	995		
0.745	41.6564	995		
0.746	41.9206	995		
0.747	42.1854	995		
0.748	42.4508	995		
0.749	42.7168	995		
0.750	42.9834	995		
0.751	43.2506	995		
0.752	43.5184	995		
0.753	43.7868	995		
0.754	44.0558	995		
0.755	44.3254	995		
0.756	44.5956	995		
0.757	44.8664	995		
0.758	45.1378	995		
0.759	45.4098	995		
0.760	45.6824	995		
0.761	45.9556	995		
0.762	46.2294	995		
0.763	46.5038	995		
0.764	46.7788	995		
0.765	47.0544	995		
0.766	47.3306	995		
0.767	47.6074	995		
0.768	47.8848	995		
0.769	48.1628	995		
0.770	48.4414	995		
0.771	48.7206	995		
0.772	49.0004	995		
0.773	49.2808	995		
0.774	49.5618	995		
0.775	49.8434	995		
0.776	50.1256	995		
0.777	50.4084	995		
0.778	50.6918	995		
0.779	50.9758	995		
0.780	51.2604	995		
0.781	51.5456	995		
0.782	51.8314	995		
0.783	52.1178	995		
0.784	52.4048	995		
0.785	52.6924	995		
0.786	52.9806	995		
0.787	53.2694	995		
0.788	53.5588	995		
0.789	53.8488	995		
0.790	54.1394	995		
0.791	54.4306	995		
0.792	54.7224	995		

TABLE IV PRESSURE TRAVERSE DATA (MEASURED TOTAL PRESSURES AND INFERRED STATIC PRESSURES) (CONT.)

STATION NO. C8 z = 31.8 cm z = 0.0 cm					
$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}}$ = .306					
r, cm	y/d	$\frac{P_{Q_{ref}}}{\rho Q_{ref}}$	$\frac{P - P_w}{\rho Q_{ref}}$	$\frac{P - P_w}{\rho Q_{ref}}$	γ_p
0	0	306			
.022	0.0020	305			
.047	.0043	304			
.072	.0066	302			
.098	.0089	301			1
.123	.0112	300			1
.149	.0135	299			1
.175	.0158	298			
.200	.0182	297			
.225	.0205	296			
.250	.0228	295			
.275	.0251	294			
.300	.0274	293			
.325	.0297	292			
.350	.0320	291			
.375	.0343	290			
.400	.0366	289			
.425	.0389	288			
.450	.0412	287			
.475	.0435	286			
.500	.0458	285			
.525	.0481	284			
.550	.0504	283			
.575	.0527	282			
.600	.0550	281			
.625	.0573	280			
.650	.0596	279			
.675	.0619	278			
.700	.0642	277			
.725	.0665	276			
.750	.0688	275			
.775	.0711	274			
.800	.0734	273			
.825	.0757	272			
.850	.0780	271			
.875	.0803	270			
.900	.0826	269			
.925	.0849	268			
.950	.0872	267			
.975	.0895	266			
1.000	.0918	265			
1.025	.0941	264			
1.050	.0964	263			
1.075	.0987	262			
1.100	.1010	261			
1.125	.1033	260			
1.150	.1056	259			
1.175	.1079	258			
1.200	.1102	257			
1.225	.1125	256			
1.250	.1148	255			
1.275	.1171	254			
1.300	.1194	253			
1.325	.1217	252			
1.350	.1240	251			
1.375	.1263	250			
1.400	.1286	249			
1.425	.1309	248			
1.450	.1332	247			
1.475	.1355	246			
1.500	.1378	245			
1.525	.1401	244			
1.550	.1424	243			
1.575	.1447	242			
1.600	.1470	241			
1.625	.1493	240			
1.650	.1516	239			
1.675	.1539	238			
1.700	.1562	237			
1.725	.1585	236			
1.750	.1608	235			
1.775	.1631	234			
1.800	.1654	233			
1.825	.1677	232			
1.850	.1700	231			
1.875	.1723	230			
1.900	.1746	229			
1.925	.1769	228			
1.950	.1792	227			
1.975	.1815	226			
2.000	.1838	225			
2.025	.1861	224			
2.050	.1884	223			
2.075	.1907	222			
2.100	.1930	221			
2.125	.1953	220			
2.150	.1976	219			
2.175	.1999	218			
2.200	.2022	217			
2.225	.2045	216			
2.250	.2068	215			
2.275	.2091	214			
2.300	.2114	213			
2.325	.2137	212			
2.350	.2160	211			
2.375	.2183	210			
2.400	.2206	209			
2.425	.2229	208			
2.450	.2252	207			
2.475	.2275	206			
2.500	.2298	205			
2.525	.2321	204			
2.550	.2344	203			
2.575	.2367	202			
2.600	.2390	201			
2.625	.2413	200			
2.650	.2436	199			
2.675	.2459	198			
2.700	.2482	197			
2.725	.2505	196			
2.750	.2528	195			
2.775	.2551	194			
2.800	.2574	193			
2.825	.2597	192			
2.850	.2620	191			
2.875	.2643	190			
2.900	.2666	189			
2.925	.2689	188			
2.950	.2712	187			
2.975	.2735	186			
3.000	.2758	185			
3.025	.2781	184			
3.050	.2804	183			
3.075	.2827	182			
3.100	.2850	181			
3.125	.2873	180			
3.150	.2896	179			
3.175	.2919	178			
3.200	.2942	177			
3.225	.2965	176			
3.250	.2988	175			
3.275	.3011	174			
3.300	.3034	173			
3.325	.3057	172			
3.350	.3080	171			
3.375	.3103	170			
3.400	.3126	169			
3.425	.3149	168			
3.450	.3172	167			
3.475	.3195	166			
3.500	.3218	165			
3.525	.3241	164			
3.550	.3264	163			
3.575	.3287	162			
3.600	.3310	161			
3.625	.3333	160			
3.650	.3356	159			
3.675	.3379	158			
3.700	.3402	157			
3.725	.3425	156			
3.750	.3448	155			
3.775	.3471	154			
3.800	.3494	153			
3.825	.3517	152			
3.850	.3540	151			
3.875	.3563	150			
3.900	.3586	149			
3.925	.3609	148			
3.950	.3632	147			
3.975	.3655	146			
4.000	.3678	145			
4.025	.3701	144			
4.050	.3724	143			
4.075	.3747	142			
4.100	.3770	141			
4.125	.3793	140			
4.150	.3816	139			
4.175	.3839	138			
4.200	.3862	137			
4.225	.3885	136			
4.250	.3908	135			
4.275	.3931	134			
4.300	.3954	133			
4.325	.3977	132			
4.350	.4000	131			
4.375	.4023	130			
4.400	.4046	129			
4.425	.4069	128			
4.450	.4092	127			
4.475	.4115	126			
4.500	.4138	125			
4.525	.4161	124			
4.550	.4184	123			
4.575	.4207	122			
4.600	.4230	121			
4.625	.4253	120			
4.650	.4276	119			
4.675	.4299	118			
4.700	.4322	117			
4.725	.4345	116			
4.750	.4368	115			
4.775	.4391	114			
4.800	.4414	113			
4.825	.4437	112			
4.850	.4460	111			
4.875	.4483	110			
4.900	.4506	109			
4.925	.4529	108			
4.950	.4552	107			
4.975	.4575	106			
5.000	.4598	105			
5.025	.4621	104			
5.050	.4644	103			
5.075	.4667	102			
5.100	.4690	101			
5.125	.4713	100			
5.150	.4736	99			
5.175	.4759	98			
5.200	.4782	97			
5.225	.4805	96			
5.250	.4828	95			
5.275	.4851	94			
5.300	.4874	93			
5.325	.4897	92			
5.350	.4920	91			
5.375	.4943	90			
5.400	.4966	89			
5.425	.4989	88			
5.450	.5012	87			
5.475	.5035	86			
5.500	.5058	85			
5.525	.5081	84			
5.550	.5104	83			
5.575	.5127	82			
5.600	.5150	81			
5.625	.5173	80			
5.650	.5196	79			
5.675	.5219	78			
5.700	.5242	77			
5.725	.5265	76			
5.750	.5288	75			
5.775	.5311	74			
5.800	.5334	73			
5.825	.5357	72			
5.850	.5380	71			
5.875	.5403	70			
5.900	.5426	69			
5.925	.5449	68			
5.950	.5472	67			
5.975	.5495	66			
6.000	.5518	65			
6.025	.5541	64			
6.050	.5564	63			
6.075	.5587	62			
6.100	.5610	61			
6.125	.5633	60			
6.150	.5656	59			
6.175	.5679	58			
6.200	.5702	57			
6.225	.5725	56			
6.250	.5748	55			
6.275	.5771	54			
6.300	.5794	53			
6.325	.5817	52			
6.350	.5840	51			
6.375	.5863	50			
6.400	.5886	49			
6.425	.5909	48			
6.450	.5932	47			
6.475	.5955	46			
6.500	.5978	45			
6.525	.6001	44			
6.550	.6024	43			
6.575	.6047	42			
6.600	.6070	41			
6.625	.6093	40			
6.650	.6116	39			
6.675	.6139	38			
6.700	.6162	37			
6.725	.6185	36			
6.750	.6208	35			
6.775	.6231	34			
6.800	.6254	33			
6.825	.6277	32			
6.850	.6300	31			
6.875	.6323	30			
6.900	.6346	29			
6.925	.6369	28			

TABLE IV. PRESSURE TRAVERSE DATA (MEASURED TOTAL PRESSURES AND INFERRED STATIC PRESSURES) (CONT.)

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TABLE IV PRESSURE TRAVERSE DATA (MEASURED TOTAL PRESSURES AND INFERRED STATIC PRESSURES) (CONT.)

STATION NO. C19 == 71.1 cm z = 0.0 cm				
$\psi_{\text{m}} - \psi_{\text{ref}} \text{ } \psi_{\text{Oref}} = .418$				
y, cm	y/d	ψ/ψ_{ref}	$\psi - \psi_{\text{ref}}/\psi_{\text{Oref}}$	7p
0	0		.418	
.07	.0015		.423	
.14	.003		.43	
.21	.0045		.435	
.28	.006		.438	
.35	.0075		.441	
.42	.009		.444	
.49	.0105		.447	
.56	.012		.449	
.63	.0135		.451	
.70	.015		.454	
.77	.0165		.457	
.84	.018		.46	
.91	.0195		.463	
.98	.021		.466	
1.05	.0225		.469	
1.12	.024		.472	
1.19	.0255		.475	
1.26	.027		.478	
1.33	.0285		.481	
1.40	.03		.484	
1.47	.0315		.487	
1.54	.033		.49	
1.61	.0345		.493	
1.68	.036		.496	
1.75	.0375		.499	
1.82	.039		.502	
1.89	.0405		.505	
1.96	.042		.508	
2.03	.0435		.511	
2.10	.045		.514	
2.17	.0465		.517	
2.24	.048		.52	
2.31	.0495		.523	
2.38	.051		.526	
2.45	.0525		.529	
2.52	.054		.532	
2.59	.0555		.535	
2.66	.057		.538	
2.73	.0585		.541	
2.80	.06		.544	
2.87	.0615		.547	
2.94	.063		.55	
3.01	.0645		.553	
3.08	.066		.556	
3.15	.0675		.559	
3.22	.069		.562	
3.29	.0705		.565	
3.36	.072		.568	
3.43	.0735		.571	
3.50	.075		.574	
3.57	.0765		.577	
3.64	.078		.58	
3.71	.0795		.583	
3.78	.081		.586	
3.85	.0825		.589	
3.92	.084		.592	
3.99	.0855		.595	
4.06	.087		.598	
4.13	.0885		.601	
4.20	.09		.604	
4.27	.0915		.607	
4.34	.093		.61	
4.41	.0945		.613	
4.48	.096		.616	
4.55	.0975		.619	
4.62	.099		.622	
4.69	.1005		.625	
4.76	.102		.628	
4.83	.1035		.631	
4.90	.105		.634	
4.97	.1065		.637	
5.04	.108		.64	
5.11	.1095		.643	
5.18	.111		.646	
5.25	.1125		.649	
5.32	.114		.652	
5.39	.1155		.655	
5.46	.117		.658	
5.53	.1185		.661	
5.60	.12		.664	
5.67	.1215		.667	
5.74	.123		.67	
5.81	.1245		.673	
5.88	.126		.676	
5.95	.1275		.679	
6.02	.129		.682	
6.09	.1305		.685	
6.16	.132		.688	
6.23	.1335		.691	
6.30	.135		.694	
6.37	.1365		.697	
6.44	.138		.7	
6.51	.1395		.703	
6.58	.141		.706	
6.65	.1425		.709	
6.72	.144		.712	
6.79	.1455		.715	
6.86	.147		.718	
6.93	.1485		.721	
7.00	.15		.724	
7.07	.1515		.727	
7.14	.153		.73	

STATION NO.	C18	==	67.3	cm±±	0.0	cm
$\psi_{\text{m}} - \psi_{\text{ref}} \text{ } ^\circ\text{Q}_{\text{ref}} = .417$						
r. cm	y/b	$\rho/\text{Q}_{\text{ref}}$	$ \psi - \psi_{\text{ref}} /\text{Q}_{\text{ref}}$	γ_p		
0	0.0015	.417				
.067	.0031	.428				
.077	.0031	.423				.998
.088	.0031	.428				1
.123	.0048	.431				1
.149	.0048	.433				
.156	.0060	.433				
.177	.0080	.439				
.177	.0121	.439				
.204	.0162	.439			.417	1
.204	.0245	.441			1	1
.204	.0245	.441			1	1
.204	.0326	.44			.416	1
.227	.0408	.44				.996
1.52	.0489	.439				
2.78	.0551	.437				
2.78	.0551	.437				
2.78	.0732	.433				
2.78	.0732	.433				
2.54	.0816	.432			.412	.993
2.79	.0897	.432				
3.05	.0979	.43			.961	
3.05	.0979	.43				
3.18	.1060	.428			.951	
3.18	.1223	.427			.92	
3.18	.1223	.427			.887	
4.06	.1305	.425			.415	
4.32	.1387	.425			.89	
4.32	.1568	.422				
5.08	.1631	.42			.413	.844
5.33	.1713	.419				
5.33	.1794	.418				
5.84	.1876	.417				
6.35	.1958	.414				
6.35	.2039	.414				.737
6.60	.2121	.415				
7.11	.2284	.412				
7.37	.2365	.412				
7.37	.2529	.412			.41	.408
7.62	.2572	.413				
8.13	.2610	.415				
8.38	.2692	.413				
8.64	.2773	.419			.422	.494
8.64	.2855	.425				
9.02	.2937	.423			.42	.599
9.02	.3023	.423				
10.8	.3467	.436				
11.4	.3670	.457				
12.1	.3874	.471			.441	.823
12.1	.4078	.486				
12.7	.4282	.518				
14.0	.4486	.546				
14.6	.4690	.554			.46	.958
15.2	.4894	.554				
15.9	.5098	.573				
15.9	.5302	.586				
16.7	.5506	.594			.488	.964
17.8	.5710	.606				
18.4	.5914	.617				
19.1	.6117	.699				
19.7	.6321	.727			.522	1
20.0	.6525	.751				
21.6	.6933	.788				
22.2	.7137	.833				
22.5	.7341	.882				
24.1	.7545	.882				
24.1	.7749	.897				
25.4	.7953	.917			.59	1
25.4	.8157	.936				
26.0	.8361	.945				
26.7	.8564	.937				
27.3	.8768	.965			.661	1
27.3	.8972	.978				
28.6	.9176	.986				
29.2	.9380	.981			.76	1
29.8	.9584	.986				
30.5	.9788	.991			.699	1
31.1	.9992	.991				
31.4	1.0196	.994				
32.0	1.0400	.994				
33.0	1.0604	.994				
33.3	1.0811	.995				
33.7	1.1018	.994				
34.3	1.1225	.994				
34.9	1.1432	.994				
35.5	1.1639	.995				
36.8	1.1846	.997				

STATION NO. C17 $z = 63.5 \text{ cm} \pm 0.0 \text{ cm}$					
$\Psi_{\text{m}} - \Psi_{\text{ref}} \quad \text{H}_2\text{O}_{\text{ref}} = .413$					
z, cm	y/d	ρ/ρ_{ref}	$\Psi - \Psi_{\text{ref}}$	$\Psi - \Psi_{\text{ref}}/\text{H}_2\text{O}_{\text{ref}}$	γ_p
0	0	.413			
.07	.0016	.423			
.14	.0032	.432			
.21	.0048	.441			
.28	.0064	.431			
.35	.0080	.432			
.42	.0096	.433			
.49	.0112	.434			
.56	.0128	.436			
.63	.0144	.437			
.70	.0160	.437			
.77	.0176	.435			
.84	.0192	.435			
.91	.0208	.437			
.98	.0224	.437			
1.05	.0240	.437			
1.12	.0256	.437			
1.19	.0272	.437			
1.26	.0288	.431			
1.33	.0304	.431			
1.40	.0320	.431			
1.47	.0336	.431			
1.54	.0352	.431			
1.61	.0368	.431			
1.68	.0384	.431			
1.75	.0400	.431			
1.82	.0416	.431			
1.89	.0432	.431			
1.96	.0448	.431			
2.03	.0464	.431			
2.10	.0480	.431			
2.17	.0496	.431			
2.24	.0512	.431			
2.31	.0528	.431			
2.38	.0544	.431			
2.45	.0560	.431			
2.52	.0576	.431			
2.59	.0592	.431			
2.66	.0608	.431			
2.73	.0624	.431			
2.80	.0640	.431			
2.87	.0656	.431			
2.94	.0672	.431			
3.01	.0688	.431			
3.08	.0704	.431			
3.15	.0720	.431			
3.22	.0736	.431			
3.29	.0752	.431			
3.36	.0768	.431			
3.43	.0784	.431			
3.50	.0800	.431			
3.57	.0816	.431			
3.64	.0832	.431			
3.71	.0848	.431			
3.78	.0864	.431			
3.85	.0880	.431			
3.92	.0896	.431			
3.99	.0912	.431			
4.06	.0928	.431			
4.13	.0944	.431			
4.20	.0960	.431			
4.27	.0976	.431			
4.34	.0992	.431			
4.41	.1008	.431			
4.48	.1024	.431			
4.55	.1040	.431			
4.62	.1056	.431			
4.69	.1072	.431			
4.76	.1088	.431			
4.83	.1104	.431			
4.90	.1120	.431			
4.97	.1136	.431			
5.04	.1152	.431			
5.11	.1168	.431			
5.18	.1184	.431			
5.25	.1200	.431			
5.32	.1216	.431			
5.39	.1232	.431			
5.46	.1248	.431			
5.53	.1264	.431			
5.60	.1280	.431			
5.67	.1296	.431			
5.74	.1312	.431			
5.81	.1328	.431			
5.88	.1344	.431			
5.95	.1360	.431			
6.02	.1376	.431			
6.09	.1392	.431			
6.16	.1408	.431			
6.23	.1424	.431			
6.30	.1440	.431			
6.37	.1456	.431			
6.44	.1472	.431			
6.51	.1488	.431			
6.58	.1504	.431			
6.65	.1520	.431			
6.72	.1536	.431			
6.79	.1552	.431			
6.86	.1568	.431			
6.93	.1584	.431			
7.00	.1600	.431			
7.07	.1616	.431			
7.14	.1632	.431			
7.21	.1648	.431			
7.28	.1664	.431			
7.35	.1680	.431			
7.42	.1696	.431			
7.49	.1712	.431			
7.56	.1728	.431			
7.63	.1744	.431			
7.70	.1760	.431			
7.77	.1776	.431			
7.84	.1792	.431			
7.91	.1808	.431			
7.98	.1824	.431			
8.05	.1840	.431			
8.12	.1856	.431			
8.19	.1872	.431			
8.26	.1888	.431			
8.33	.1904	.431			
8.40	.1920	.431			
8.47	.1936	.431			
8.54	.1952	.431			
8.61	.1968	.431			
8.68	.1984	.431			
8.75	.2000	.431			
8.82	.2016	.431			
8.89	.2032	.431			
8.96	.2048	.431			
9.03	.2064	.431			
9.10	.2080	.431			
9.17	.2096	.431			
9.24	.2112	.431			
9.31	.2128	.431			
9.38	.2144	.431			
9.45	.2160	.431			
9.52	.2176	.431			
9.59	.2192	.431			
9.66	.2208	.431			
9.73	.2224	.431			
9.80	.2240	.431			
9.87	.2256	.431			
9.94	.2272	.431			
10.01	.2288	.431			
10.08	.2304	.431			
10.15	.2320	.431			
10.22	.2336	.431			
10.29	.2352	.431			
10.36	.2368	.431			
10.43	.2384	.431			
10.50	.2400	.431			
10.57	.2416	.431			
10.64	.2432	.431			
10.71	.2448	.431			
10.78	.2464	.431			
10.85	.2480	.431			
10.92	.2496	.431			
10.99	.2512	.431			
11.06	.2528	.431			
11.13	.2544	.431			
11.20	.2560	.431			
11.27	.2576	.431			
11.34	.2592	.431			
11.41	.2608	.431			
11.48	.2624	.431			
11.55	.2640	.431			
11.62	.2656	.431			
11.69	.2672	.431			
11.76	.2688	.431			
11.83	.2704	.431			
11.90	.2720	.431			
11.97	.2736	.431			
12.04	.2752	.431			
12.11	.2768	.431			
12.18	.2784	.431			
12.25	.2800	.431			
12.32	.2816	.431			
12.39	.2832	.431			
12.46	.2848	.431			
12.53	.2864	.431			
12.60	.2880	.431			
12.67	.2896	.431			
12.74	.2912	.431			
12.81	.2928	.431			
12.88	.2944	.431			
12.95	.2960	.431			
13.02	.2976	.431			
13.09	.2992	.431			
13.16	.3008	.431			
13.23	.3024	.431			
13.30	.3040	.431			
13.37	.3056	.431			
13.44	.3072	.431			
13.51	.3088	.431			
13.58	.3104	.431			
13.65	.3120	.431			
13.72	.3136	.431			
13.79	.3152	.431			
13.86	.3168	.431			
13.93	.3184	.431			
14.00	.3200	.431			
14.07	.3216	.431			
14.14	.3232	.431			
14.21	.3248	.431			
14.28	.3264	.431			
14.35	.3280	.431			
14.42	.3296	.431			
14.49	.3312	.431			
14.56	.3328	.431			
14.63	.3344	.431			
14.70	.3360	.431			
14.77	.3376	.431			
14.84	.3392	.431			
14.91	.3408	.431			
14.98	.3424	.431			
15.05	.3440	.431			
15.12	.3456	.431			
15.19	.3472	.431			
15.26	.3488	.431			
15.33	.3504	.431			
15.40	.3520	.431			
15.47	.3536	.431			
15.54	.3552	.431			
15.61	.3568	.431			
15.68	.3584	.431			
15.75	.3600	.431			
15.82	.3616	.431			
15.89	.3632	.431			
15.96	.3648	.431			
16.03	.3664	.431			
16.10	.3680	.431			
16.17	.3696	.431			
16.24	.3712	.431			
16.31	.3728	.431			
16.38	.3744	.431			
16.45	.3760	.431			
16.52	.3776	.431			
16.59	.3792	.431			
16.66	.3808	.431			
16.73	.3824	.431			
16.80	.3840	.431			
16.87	.3856	.431			
16.94	.3872	.431			
17.01	.3888	.431			
17.08	.3904	.431			
17.15	.3920	.431			
17.22	.3936	.431			
17.29	.3952	.431			
17.36	.3968	.431			
17.43	.3984	.431			
17.50	.4000	.431			
17.57	.4016	.431			
17.64	.4032	.431			
17.71	.4048	.431			
17.78	.4064	.431			
17.85	.4080	.431			
17.92	.4096	.431			
17.99	.4112	.431			
18.06	.4128	.431			
18.13	.4144	.431			
18.20	.4160	.431			
18.27	.4176	.431			
18.34	.4192	.431			
18.41	.4208	.431			
18.48	.4224	.431			
18.55	.4240	.431			
18.62	.4256	.431			
18.69	.4272	.431			
18.76	.4288	.431			
18.83	.4304	.431			
18.90	.4320	.431			
18.97	.4336	.431			
19.04	.4352	.431			
19.11	.4368	.431			
19.18	.4384	.431			
19.25	.4400	.431			
19.32	.4416	.431			
19.39	.4432	.431			
19.46	.4448	.431			
19.53	.4464	.431			
19.60	.4480	.431			
19.67	.4496	.431			
19.74	.4512	.431			
19.81	.4528	.431			
19.88	.4544	.431			
19.95	.4560	.431			
20.02	.4576	.431			
20.09	.459				

STATION NO. C16 z = 59.7 cm z = 0.0 cm						
$\varphi_w - \varphi_{w0} \quad Q_{w0} = .422$						
z, cm	y/d	P/Q_{w0}	$\varphi - \varphi_w / Q_{w0} $	γ_p		
0	0	.422				
0.047	.0019	.43				
.072	.0039	.434				.884
.093	.0054	.436				
.119	.0069	.437				.924
.159	.0080	.438				.93
.209	.0101	.439				
.259	.0123	.44				.959
.304	.0203	.441				.969
.354	.0255	.442				.981
.402	.0306	.442				
.452	.0408	.44				.981
.502	.0517	.438				.929
.552	.0614	.438				
.602	.0714	.436				.89
.652	.0816	.436				
.702	.0918	.436			.424	
.752	.1020	.432				
.802	.1124	.432				.82
.852	.1224	.432				
.902	.1327	.429				.86
.952	.1429	.429				.708
1.002	.1531	.429				.695
1.052	.1633	.429				
1.102	.1737	.429				.695
1.152	.1837	.429				
1.202	.1939	.429				.642
1.252	.2041	.421				
1.302	.2143	.421			.418	.469
1.352	.2245	.421				
1.402	.2347	.421				
1.452	.2449	.421				
1.502	.2551	.421			.425	
1.552	.2653	.421				
1.602	.2755	.421			.423	.752
1.652	.2857	.421			.422	.802
1.702	.2959	.421			.411	
1.752	.3061	.421				.934
1.802	.3163	.421				
1.852	.3265	.421				
1.902	.3367	.421				
1.952	.3469	.421				
2.002	.3571	.421				
2.052	.3673	.421				
2.102	.3775	.421				
2.152	.3877	.421				
2.202	.3979	.421				
2.252	.4081	.421				
2.302	.4183	.421				
2.352	.4285	.421				
2.402	.4387	.421				
2.452	.4489	.421			.451	.977
2.502	.4591	.421				
2.552	.4693	.421				
2.602	.4795	.421				
2.652	.4897	.421				
2.702	.4999	.421				
2.752	.5101	.421				
2.802	.5203	.421				
2.852	.5305	.421				
2.902	.5407	.421				
2.952	.5509	.421				
3.002	.5611	.421				
3.052	.5713	.421				
3.102	.5815	.421				
3.152	.5917	.421				
3.202	.6019	.421				
3.252	.6121	.421				
3.302	.6223	.421				
3.352	.6325	.421				
3.402	.6427	.421				
3.452	.6529	.421				
3.502	.6631	.421				
3.552	.6733	.421				
3.602	.6835	.421				
3.652	.6937	.421				
3.702	.7039	.421				
3.752	.7141	.421				
3.802	.7243	.421				
3.852	.7345	.421				
3.902	.7447	.421				
3.952	.7549	.421				
4.002	.7651	.421				
4.052	.7753	.421				
4.102	.7855	.421				
4.152	.7957	.421				
4.202	.8059	.421				
4.252	.8161	.421				
4.302	.8263	.421				
4.352	.8365	.421				
4.402	.8467	.421				
4.452	.8569	.421				
4.502	.8671	.421				
4.552	.8773	.421				
4.602	.8875	.421				
4.652	.8977	.421				
4.702	.9079	.421				
4.752	.9181	.421				
4.802	.9283	.421				
4.852	.9385	.421				
4.902	.9487	.421				
4.952	.9589	.421				
5.002	.9691	.421				
5.052	.9793	.421				
5.102	.9895	.421				
5.152	.9997	.421				
5.202	1.0099	.421				
5.252	1.0201	.421				
5.302	1.0303	.421				
5.352	1.0405	.421				
5.402	1.0507	.421				
5.452	1.0609	.421				
5.502	1.0711	.421				
5.552	1.0813	.421				
5.602	1.0915	.421				
5.652	1.1017	.421				
5.702	1.1119	.421				
5.752	1.1221	.421				
5.802	1.1323	.421				
5.852	1.1425	.421				
5.902	1.1527	.421				
5.952	1.1629	.421				
6.002	1.1731	.421				
6.052	1.1833	.421				
6.102	1.1935	.421				
6.152	1.2037	.421				
6.202	1.2139	.421				
6.252	1.2241	.421				
6.302	1.2343	.421				
6.352	1.2445	.421				
6.402	1.2547	.421				
6.452	1.2649	.421				
6.502	1.2751	.421				
6.552	1.2853	.421				
6.602	1.2955	.421				
6.652	1.3057	.421				
6.702	1.3159	.421				
6.752	1.3261	.421				
6.802	1.3363	.421				
6.852	1.3465	.421				
6.902	1.3567	.421				
6.952	1.3669	.421				
7.002	1.3771	.421				
7.052	1.3873	.421				
7.102	1.3975	.421				
7.152	1.4077	.421				
7.202	1.4179	.421				
7.252	1.4281	.421				
7.302	1.4383	.421				
7.352	1.4485	.421				
7.402	1.4587	.421				
7.452	1.4689	.421				
7.502	1.4791	.421				
7.552	1.4893	.421				
7.602	1.4995	.421				
7.652	1.5097	.421				
7.702	1.5199	.421				
7.752	1.5301	.421				
7.802	1.5403	.421				
7.852	1.5505	.421				
7.902	1.5607	.421				
7.952	1.5709	.421				
8.002	1.5811	.421				
8.052	1.5913	.421				
8.102	1.6015	.421				
8.152	1.6117	.421				
8.202	1.6219	.421				
8.252	1.6321	.421				
8.302	1.6423	.421				
8.352	1.6525	.421				
8.402	1.6627	.421				
8.452	1.6729	.421				
8.502	1.6831	.421				
8.552	1.6933	.421				
8.602	1.7035	.421				
8.652	1.7137	.421				
8.702	1.7239	.421				
8.752	1.7341	.421				
8.802	1.7443	.421				
8.852	1.7545	.421				
8.902	1.7647	.421				
8.952	1.7749	.421				
9.002	1.7851	.421				
9.052	1.7953	.421				
9.102	1.8055	.421				
9.152	1.8157	.421				
9.202	1.8259	.421				
9.252	1.8361	.421				
9.302	1.8463	.421				
9.352	1.8565	.421				
9.402	1.8667	.421				
9.452	1.8769	.421				
9.502	1.8871	.421				
9.552	1.8973	.421				
9.602	1.9075	.421				
9.652	1.9177	.421				
9.702	1.9279	.421				
9.752	1.9381	.421				
9.802	1.9483	.421				
9.852	1.9585	.421				
9.902	1.9687	.421				
9.952	1.9789	.421				
10.002	1.9891	.421				
10.052	1.9993	.421				
10.102	2.0095	.421				
10.152	2.0197	.421				
10.202	2.0299	.421				
10.252	2.0401	.421				
10.302	2.0503	.421				
10.352	2.0605	.421				
10.402	2.0707	.421				
10.452	2.0809	.421				
10.502	2.0911	.421				
10.552	2.1013	.421				
10.602	2.1115	.421				
10.652	2.1217	.421				
10.702	2.1319	.421				
10.752	2.1421	.421				
10.802	2.1523	.421				
10.852	2.1625	.421				
10.902	2.1727	.421				
10.952	2.1829	.421				
11.002	2.1931	.421				
11.052	2.2033	.421				
11.102	2.2135	.421				
11.152	2.2237	.421				
11.202	2.2339	.421				
11.252	2.2441	.421				
11.302	2.2543	.421				
11.352	2.2645	.421				
11.402	2.2747	.421				
11.452	2.2849	.421				
11.502	2.2951	.421				
11.552	2.3053	.421				
11.602	2.3155	.421				
11.652	2.3257	.421				
11.702	2.3359	.421				
11.752	2.3461	.421				
11.802	2.3563	.421				
11.852	2.3665	.421				
11.902	2.3767	.421				
11.952	2.3869	.421				
12.002	2.3971	.421				
12.052	2.4073	.421				
12.102	2.4175	.421				
12.152	2.4277	.421				
12.202	2.4379	.421				
12.252	2.4481	.421				
12.302	2.4583	.421				
12.352	2.4685	.421				
12.402	2.4787	.421				
12.452	2.4889	.421				</

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STATION NO. C20 z = 74.9 cm z = 0.0 cm									
$\frac{P_{ref} - P_{ref}}{P_{ref}} = .418$									
y, cm	y/d	P, ref	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$	$\frac{P_{ref} - P_{ref}}{P_{ref}}$
0	0	.418							
0.022	.0006	.424							
.047	.0014	.436							
.072	.0021	.442							
.098	.0028	.448							
.123	.0036	.454							
.149	.0044	.460							
.175	.0052	.466							
.200	.0059	.472							
.226	.0067	.478							
.250	.0074	.483							
.276	.0082	.489							
.300	.0089	.495							
.326	.0097	.501							
.350	.0104	.506							
.376	.0112	.512							
.400	.0119	.518							
.426	.0127	.524							
.450	.0134	.530							
.476	.0142	.536							
.500	.0149	.542							
.526	.0157	.548							
.550	.0164	.554							
.576	.0172	.560							
.600	.0179	.566							
.626	.0187	.572							
.650	.0194	.578							
.676	.0202	.584							
.700	.0209	.590							
.726	.0217	.596							
.750	.0224	.602							
.776	.0232	.608							
.800	.0239	.614							
.826	.0247	.620							
.850	.0254	.626							
.876	.0262	.632							
.900	.0269	.638							
.926	.0277	.644							
.950	.0284	.650							
.976	.0292	.656							
1.000	.0299	.662							
1.026	.0307	.668							
1.050	.0314	.674							
1.076	.0322	.680							
1.100	.0329	.686							
1.126	.0337	.692							
1.150	.0344	.698							
1.176	.0352	.704							
1.200	.0359	.710							
1.226	.0367	.716							
1.250	.0374	.722							
1.276	.0382	.728							
1.300	.0389	.734							
1.326	.0397	.740							
1.350	.0404	.746							
1.376	.0412	.752							
1.400	.0419	.758							
1.426	.0427	.764							
1.450	.0434	.770							
1.476	.0442	.776							
1.500	.0449	.782							
1.526	.0457	.788							
1.550	.0464	.794							
1.576	.0472	.800							
1.600	.0479	.806							
1.626	.0487	.812							
1.650	.0494	.818							
1.676	.0502	.824							
1.700	.0509	.830							
1.726	.0517	.836							
1.750	.0524	.842							
1.776	.0532	.848							
1.800	.0539	.854							
1.826	.0547	.860							
1.850	.0554	.866							
1.876	.0562	.872							
1.900	.0569	.878							
1.926	.0577	.884							
1.950	.0584	.890							
1.976	.0592	.896							
2.000	.0599	.902							
2.026	.0607	.908							
2.050	.0614	.914							
2.076	.0622	.920							
2.100	.0629	.926							
2.126	.0637	.932							
2.150	.0644	.938							
2.176	.0652	.944							
2.200	.0659	.950							
2.226	.0667	.956							
2.250	.0674	.962							
2.276	.0682	.968							
2.300	.0689	.974							
2.326	.0697	.980							
2.350	.0704	.986							
2.376	.0712	.992							
2.400	.0719	.998							
2.426	.0727	1.004							
2.450	.0734	1.010							
2.476	.0742	1.016							
2.500	.0749	1.022							
2.526	.0757	1.028							
2.550	.0764	1.034							
2.576	.0772	1.040							
2.600	.0779	1.046							
2.626	.0787	1.052							
2.650	.0794	1.058							
2.676	.0802	1.064							
2.700	.0809	1.070							
2.726	.0817	1.076							
2.750	.0824	1.082							
2.776	.0832	1.088							
2.800	.0839	1.094							
2.826	.0847	1.100							
2.850	.0854	1.106							
2.876	.0862	1.112							
2.900	.0869	1.118							
2.926	.0877	1.124							
2.950	.0884	1.130							
2.976	.0892	1.136							
3.000	.0899	1.142							
3.026	.0907	1.148							
3.050	.0914	1.154							
3.076	.0922	1.160							
3.100	.0929	1.166							
3.126	.0937	1.172							
3.150	.0944	1.178							
3.176	.0952	1.184							
3.200	.0959	1.190							
3.226	.0967	1.196							
3.250	.0974	1.202							
3.276	.0982	1.208							
3.300	.0989	1.214							
3.326	.0997	1.220							
3.350	.1004	1.226							
3.376	.1012	1.232							
3.400	.1019	1.238							
3.426	.1027	1.244							
3.450	.1034	1.250							
3.476	.1042	1.256							
3.500	.1049	1.262							
3.526	.1057	1.268							
3.550	.1064	1.274							
3.576	.1072	1.280							
3.600	.1079	1.286							
3.626	.1087	1.292							
3.650	.1094	1.298							
3.676	.1102	1.304							
3.700	.1109	1.310							
3.726	.1117	1.316							
3.750	.1124	1.322							
3.776	.1132	1.328							
3.800	.1139	1.334							
3.826	.1147	1.340							
3.850	.1154	1.346							
3.876	.1162	1.352							
3.900	.1169	1.358							
3.926	.1177	1.364							
3.950	.1184	1.370							
3.976	.1192	1.376							
4.000	.1199	1.382							
4.026	.1207	1.388							
4.050	.1214	1.394							
4.076	.1222	1.400							
4.100	.1229	1.406							
4.126	.1237	1.412							
4.150	.1244	1.418							
4.176	.1252	1.424							
4.200	.1259	1.430							
4.226	.1267	1.436							
4.250	.1274	1.442							
4.276	.1282	1.448							
4.300	.1289	1.454							
4.326	.1297	1.460							
4.350	.1304	1.466							
4.376	.1312	1.472							
4.400	.1319	1.478							
4.426	.1327	1.484							
4.450	.1334	1.490							
4.476	.1342	1.496							
4.500	.1349	1.502							
4.526	.1357	1.508							
4.550	.1364	1.514							
4.576	.1372	1.520							
4.600	.1379	1.526							
4.626	.1387	1.532							
4.650	.1394	1.538							
4.676	.1402	1.544							
4.700	.1409	1.550							
4.726	.1417	1.556							
4.750	.1424	1.562							
4.776	.1432	1.568							
4.800	.1439	1.574							
4.826	.1447	1.580							
4.850	.1454	1.586							
4.876	.1462	1.592							
4.9									

STATION NO. C24 x = 90.2 cm z = 0.0 cm						
$\frac{P_{Q_{rel}} - P_{w_{rel}}}{\rho Q_{rel}} = .448$						
Y, cm	y/d	P/Q _{rel}	$\frac{P - P_w}{\rho Q_{rel}}$	γ_p		
0	0	.448				
.022	.0007	.437				
.047	.0016	.437				
.072	.0025	.437				
.098	.0034	.437				
.123	.0042	.478				
.149	.0051	.485				
.175	.0060	.485				
.200	.0069	.478				
.225	.0078	.478				
.250	.0087	.478				
.275	.0096	.478				
.300	.0105	.478				
.325	.0114	.484				
.350	.0123	.484				
.375	.0132	.488				
.400	.0141	.488				
.425	.0150	.488				
.450	.0159	.488				
.475	.0168	.488				
.500	.0177	.488				
.525	.0186	.488				
.550	.0195	.488				
.575	.0204	.488				
.600	.0213	.488				
.625	.0222	.488				
.650	.0231	.488				
.675	.0240	.488				
.700	.0249	.488				
.725	.0258	.488				
.750	.0267	.488				
.775	.0276	.488				
.800	.0285	.488				
.825	.0294	.488				
.850	.0303	.488				
.875	.0312	.488				
.900	.0321	.488				
.925	.0330	.488				
.950	.0339	.488				
.975	.0348	.488				
1.000	.0357	.488				
1.025	.0366	.488				
1.050	.0375	.488				
1.075	.0384	.488				
1.100	.0393	.488				
1.125	.0402	.488				
1.150	.0411	.488				
1.175	.0420	.488				
1.200	.0429	.488				
1.225	.0438	.488				
1.250	.0447	.488				
1.275	.0456	.488				
1.300	.0465	.488				
1.325	.0474	.488				
1.350	.0483	.488				
1.375	.0492	.488				
1.400	.0501	.488				
1.425	.0510	.488				
1.450	.0519	.488				
1.475	.0528	.488				
1.500	.0537	.488				
1.525	.0546	.488				
1.550	.0555	.488				
1.575	.0564	.488				
1.600	.0573	.488				
1.625	.0582	.488				
1.650	.0591	.488				
1.675	.0600	.488				
1.700	.0609	.488				
1.725	.0618	.488				
1.750	.0627	.488				
1.775	.0636	.488				
1.800	.0645	.488				
1.825	.0654	.488				
1.850	.0663	.488				
1.875	.0672	.488				
1.900	.0681	.488				
1.925	.0690	.488				
1.950	.0699	.488				
1.975	.0708	.488				
2.000	.0717	.488				
2.025	.0726	.488				
2.050	.0735	.488				
2.075	.0744	.488				
2.100	.0753	.488				
2.125	.0762	.488				
2.150	.0771	.488				
2.175	.0780	.488				
2.200	.0789	.488				
2.225	.0798	.488				
2.250	.0807	.488				
2.275	.0816	.488				
2.300	.0825	.488				
2.325	.0834	.488				
2.350	.0843	.488				
2.375	.0852	.488				
2.400	.0861	.488				
2.425	.0870	.488				
2.450	.0879	.488				
2.475	.0888	.488				
2.500	.0897	.488				
2.525	.0906	.488				
2.550	.0915	.488				
2.575	.0924	.488				
2.600	.0933	.488				
2.625	.0942	.488				
2.650	.0951	.488				
2.675	.0960	.488				
2.700	.0969	.488				
2.725	.0978	.488				
2.750	.0987	.488				
2.775	.0996	.488				
2.800	.1005	.488				
2.825	.1014	.488				
2.850	.1023	.488				
2.875	.1032	.488				
2.900	.1041	.488				
2.925	.1050	.488				
2.950	.1059	.488				
2.975	.1068	.488				
3.000	.1077	.488				
3.025	.1086	.488				
3.050	.1095	.488				
3.075	.1104	.488				
3.100	.1113	.488				
3.125	.1122	.488				
3.150	.1131	.488				
3.175	.1140	.488				
3.200	.1149	.488				
3.225	.1158	.488				
3.250	.1167	.488				
3.275	.1176	.488				
3.300	.1185	.488				
3.325	.1194	.488				
3.350	.1203	.488				
3.375	.1212	.488				
3.400	.1221	.488				

STATION NO. C25 x = 94.0 cm z = 0.0 cm						
$\frac{P_{Q_{rel}} - P_{w_{rel}}}{\rho Q_{rel}} = .466$						
Y, cm	y/d	P/Q _{rel}	$\frac{P - P_w}{\rho Q_{rel}}$	γ_p		
0	0	.466				
.022	.0008	.466				
.047	.0016	.466				
.072	.0025	.466				
.098	.0034	.466				
.123	.0042	.466				
.149	.0051	.466				
.175	.0060	.466				
.200	.0069	.466				
.225	.0078	.466				
.250	.0087	.466				
.275	.0096	.466				
.300	.0105	.466				
.325	.0114	.466				
.350	.0123	.466				
.375	.0132	.466				
.400	.0141	.466				
.425	.0150	.466				
.450	.0159	.466				
.475	.0168	.466				
.500	.0177	.466				
.525	.0186	.466				
.550	.0195	.466				
.575	.0204	.466				
.600	.0213	.466				
.625	.0222	.466				
.650	.0231	.466				
.675	.0240	.466				
.700	.0249	.466				
.725	.0258	.466				
.750	.0267	.466				
.775	.0276	.466				
.800	.0285	.466				
.825	.0294	.466				
.850	.0303	.466				
.875	.0312	.466				
.900	.0321	.466				
.925	.0330	.466				
.950	.0339	.466				
.975	.0348	.466				
1.000	.0357	.466				

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STATION NO. C33 z = 133.4 cm z = 0.0 cm				
$\frac{p_w - p_{w,ref}}{p_{Q,ref}} = .277$				
y, cm	y/d	P/Q_{ref}	$\frac{p - p_w}{p_{Q,ref}}$	γ_p
0	0	.277		
.022	.0017	.434		
.047	.0036	.572		
.072	.0073	.593		
.098	.0094	.62		
.123	.0114	.632		
.149	.0133	.653		
.175	.0153	.653		
.199	.0173	.658		
.224	.0191	.687		
.247	.0208	.696		
.271	.0235	.707		
.294	.0257	.711		
.317	.0277	.714		
.340	.0297	.706		
.363	.0315	.706		
.386	.0339	.706		
.409	.0354	.701		
.432	.0372	.701		
.455	.0391	.701		
.478	.0412	.69		
.501	.0436	.691		
.524	.0461	.691		
.547	.0488	.702		
.570	.0518	.718		
.593	.0552	.732		
.616	.0591	.754		
.639	.0635	.784		
.662	.0684	.819		
.685	.0738	.859		
.708	.0798	.868		
.731	.0864	.868		
.754	.0936	.868		
.777	.1014	.868		
.800	.1098	.868		
.823	.1188	.868		
.846	.1284	.868		
.869	.1386	.868		
.892	.1494	.868		
.915	.1608	.868		
.938	.1728	.868		
.961	.1854	.868		
.984	.1986	.868		
1.007	.2124	.868		
1.030	.2268	.868		
1.053	.2418	.868		
1.076	.2574	.868		
1.099	.2736	.868		
1.122	.2904	.868		
1.145	.3078	.868		
1.168	.3258	.868		
1.191	.3444	.868		
1.214	.3636	.868		
1.237	.3834	.868		
1.260	.4038	.868		
1.283	.4248	.868		
1.306	.4464	.868		
1.329	.4686	.868		
1.352	.4914	.868		
1.375	.5148	.868		
1.398	.5388	.868		
1.421	.5634	.868		
1.444	.5886	.868		
1.467	.6144	.868		
1.490	.6408	.868		
1.513	.6678	.868		
1.536	.6954	.868		
1.559	.7236	.868		
1.582	.7524	.868		
1.605	.7818	.868		
1.628	.8118	.868		
1.651	.8424	.868		
1.674	.8736	.868		
1.697	.9054	.868		
1.720	.9378	.868		
1.743	.9708	.868		
1.766	1.0044	.868		
1.789	1.0386	.868		
1.812	1.0734	.868		
1.835	1.1088	.868		
1.858	1.1448	.868		
1.881	1.1814	.868		
1.904	1.2186	.868		
1.927	1.2564	.868		
1.950	1.2948	.868		
1.973	1.3338	.868		
1.996	1.3734	.868		
2.019	1.4136	.868		
2.042	1.4544	.868		
2.065	1.4958	.868		
2.088	1.5378	.868		
2.111	1.5804	.868		
2.134	1.6236	.868		
2.157	1.6674	.868		
2.180	1.7118	.868		
2.203	1.7568	.868		
2.226	1.8024	.868		
2.249	1.8486	.868		
2.272	1.8954	.868		
2.295	1.9428	.868		
2.318	1.9908	.868		
2.341	2.0394	.868		
2.364	2.0886	.868		
2.387	2.1384	.868		
2.410	2.1888	.868		
2.433	2.2398	.868		
2.456	2.2914	.868		
2.479	2.3436	.868		
2.502	2.3964	.868		
2.525	2.4498	.868		
2.548	2.5038	.868		
2.571	2.5584	.868		
2.594	2.6136	.868		
2.617	2.6694	.868		
2.640	2.7258	.868		
2.663	2.7828	.868		
2.686	2.8404	.868		
2.709	2.8986	.868		
2.732	2.9574	.868		
2.755	3.0168	.868		
2.778	3.0768	.868		
2.801	3.1374	.868		
2.824	3.1986	.868		
2.847	3.2604	.868		
2.870	3.3228	.868		
2.893	3.3858	.868		
2.916	3.4494	.868		
2.939	3.5136	.868		
2.962	3.5784	.868		
2.985	3.6438	.868		
3.008	3.7098	.868		
3.031	3.7764	.868		
3.054	3.8436	.868		
3.077	3.9114	.868		
3.100	3.9798	.868		
3.123	4.0488	.868		
3.146	4.1184	.868		
3.169	4.1886	.868		
3.192	4.2594	.868		
3.215	4.3308	.868		
3.238	4.4028	.868		
3.261	4.4754	.868		
3.284	4.5486	.868		
3.307	4.6224	.868		
3.330	4.6968	.868		
3.353	4.7718	.868		
3.376	4.8474	.868		
3.399	4.9236	.868		
3.422	5.0004	.868		
3.445	5.0778	.868		
3.468	5.1558	.868		
3.491	5.2344	.868		
3.514	5.3136	.868		
3.537	5.3934	.868		
3.560	5.4738	.868		
3.583	5.5548	.868		
3.606	5.6364	.868		
3.629	5.7186	.868		
3.652	5.8014	.868		
3.675	5.8848	.868		
3.698	5.9688	.868		
3.721	6.0534	.868		
3.744	6.1386	.868		
3.767	6.2244	.868		
3.790	6.3108	.868		
3.813	6.3978	.868		
3.836	6.4854	.868		
3.859	6.5736	.868		
3.882	6.6624	.868		
3.905	6.7518	.868		
3.928	6.8418	.868		
3.951	6.9324	.868		
3.974	7.0236	.868		
3.997	7.1154	.868		
4.020	7.2078	.868		
4.043	7.3008	.868		
4.066	7.3944	.868		
4.089	7.4886	.868		
4.112	7.5834	.868		
4.135	7.6788	.868		
4.158	7.7748	.868		
4.181	7.8714	.868		
4.203	7.9686	.868		
4.226	8.0664	.868		
4.249	8.1648	.868		
4.272	8.2638	.868		
4.295	8.3634	.868		
4.318	8.4636	.868		
4.341	8.5644	.868		
4.364	8.6658	.868		
4.387	8.7678	.868		
4.410	8.8704	.868		
4.433	8.9736	.868		
4.456	9.0774	.868		
4.479	9.1818	.868		
4.502	9.2868	.868		
4.525	9.3924	.868		
4.548	9.4986	.868		
4.571	9.6054	.868		
4.594	9.7128	.868		
4.617	9.8208	.868		
4.640	9.9294	.868		
4.663	10.0386	.868		
4.686	10.1484	.868		
4.709	10.2588	.868		
4.732	10.3698	.868		
4.755	10.4814	.868		
4.778	10.5936	.868		
4.801	10.7064	.868		
4.824	10.8198	.868		
4.847	10.9338	.868		
4.870	11.0484	.868		
4.893	11.1636	.868		
4.916	11.2794	.868		
4.939	11.3958	.868		
4.962	11.5128	.868		
4.985	11.6304	.868		
5.008	11.7486	.868		
5.031	11.8674	.868		
5.054	11.9868	.868		
5.077	12.1068	.868		
5.100	12.2274	.868		
5.123	12.3486	.868		
5.146	12.4704	.868		
5.169	12.5928	.868		
5.192	12.7158	.868		
5.215	12.8394	.868		
5.238	12.9636	.868		
5.261	13.0884	.868		
5.284	13.2138	.868		
5.307	13.3398	.868		
5.330	13.4664	.868		
5.353	13.5936	.868		
5.376	13.7214	.868		
5.399	13.8498	.868		
5.422	13.9788	.868		
5.445	14.1084	.868		
5.468	14.2386	.868		
5.491	14.3694	.868		
5.514	14.5008	.868		
5.537	14.6328	.868		
5.560	14.7654	.868		
5.583	14.8986	.868		
5.606	15.0324	.868		
5.629	15.1668	.868		
5.652	15.3018	.868		
5.675	15.4374	.868		
5.698	15.5736	.868		
5.721	15.7104	.868		
5.744	15.8478	.868		
5.767	15.9858	.868		
5.790	16.1244	.868		
5.813	16.2636	.868		
5.836	16.4034	.868		
5.859	16.5438	.868		
5.882	16.6848	.868		
5.905	16.8264	.868		
5.928	16.9686	.868		
5.951	17.1114	.868		
5.974	17.2548	.868		
5.997	17.3988	.868		
6.020	17.5434	.868		
6.043	17.6886	.868		
6.066	17.8344	.868		
6.089	17.9808	.868		
6.112	18.1278	.868		
6.135	18.2754	.868		
6.158	18.4236	.868		
6.181	18.5724	.868		
6.204	18.7218	.868		
6.227	18.8718	.868		
6.250	19.0224	.868		
6.273	19.1736	.868		
6.296	19.3254	.868		
6.319	19.4778	.868		
6.342	19.6308	.868		
6.365	19.7844	.868		
6.388	19.9386	.868		
6.411	20.0934	.868		
6.434	20.2488	.868		
6.457	20.4048	.868		
6.480	20.5614	.868		
6.503	20.7186	.868		
6.526	20.8764	.868		
6.549	21.0348	.868		
6.572	21.1938	.868		
6.595	21.3534	.868		
6.618	21.5136	.868		
6.641	21.6744	.868		
6.664	21.8358	.868		
6.687	21.9978	.868		
6.710	22.1604	.868		
6.733	22.3236	.868		
6.756	22.4874	.868		
6.779	22.6518	.868		
6.802	22.8168	.868		
6.825	22.9824	.868		
6.848	23.1486	.868		
6.871	23.3154	.868		
6.894	23.4828	.868		
6.917	23.6508	.868		
6.940	23.8194	.868		
6.963</				

STATION NO. C34. $x = 140.3$ cm $z = 0.0$ cm				
$\frac{P_w - P_{ref}}{Q_{ref}} = .26$				
y , cm	y/δ	P/Q_{ref}	$(P - P_{ref})/Q_{ref}$	γ_p
0	0	.26		
.022	.0017	.499		1
.047	.0037	.555		
.072	.0057	.588		1
.098	.0077	.604		1
.123	.0097	.613		
.149	.0117	.619		1
.174	.0137	.623		
.199	.0157	.629		1
.225	.0177	.633		
.250	.0197	.637		1
.275	.0217	.641		
.300	.0237	.645		1
.325	.0257	.649		
.350	.0277	.653		1
.375	.0297	.657		
.400	.0317	.661		1
.425	.0337	.665		
.450	.0357	.669		1
.475	.0377	.673		
.500	.0397	.677		1
.525	.0417	.681		
.550	.0437	.685		1
.575	.0457	.689		
.600	.0477	.693		1
.625	.0497	.697		
.650	.0517	.701		1
.675	.0537	.705		
.700	.0557	.709		1
.725	.0577	.713		
.750	.0597	.717		1
.775	.0617	.721		
.800	.0637	.725		1
.825	.0657	.729		
.850	.0677	.733		1
.875	.0697	.737		
.900	.0717	.741		1
.925	.0737	.745		
.950	.0757	.749		1
.975	.0777	.753		
1.000	.0797	.757		1
1.025	.0817	.761		
1.050	.0837	.765		1
1.075	.0857	.769		
1.100	.0877	.773		1
1.125	.0897	.777		
1.150	.0917	.781		1
1.175	.0937	.785		
1.200	.0957	.789		1
1.225	.0977	.793		
1.250	.0997	.797		1
1.275	.1017	.801		
1.300	.1037	.805		1
1.325	.1057	.809		
1.350	.1077	.813		1
1.375	.1097	.817		
1.400	.1117	.821		1
1.425	.1137	.825		
1.450	.1157	.829		1
1.475	.1177	.833		
1.500	.1197	.837		1
1.525	.1217	.841		
1.550	.1237	.845		1
1.575	.1257	.849		
1.600	.1277	.853		1
1.625	.1297	.857		
1.650	.1317	.861		1
1.675	.1337	.865		
1.700	.1357	.869		1
1.725	.1377	.873		
1.750	.1397	.877		1
1.775	.1417	.881		
1.800	.1437	.885		1
1.825	.1457	.889		
1.850	.1477	.893		1
1.875	.1497	.897		
1.900	.1517	.901		1
1.925	.1537	.905		
1.950	.1557	.909		1
1.975	.1577	.913		
2.000	.1597	.917		1
2.025	.1617	.921		
2.050	.1637	.925		1
2.075	.1657	.929		
2.100	.1677	.933		1
2.125	.1697	.937		
2.150	.1717	.941		1
2.175	.1737	.945		
2.200	.1757	.949		1
2.225	.1777	.953		
2.250	.1797	.957		1
2.275	.1817	.961		
2.300	.1837	.965		1
2.325	.1857	.969		
2.350	.1877	.973		1
2.375	.1897	.977		
2.400	.1917	.981		1
2.425	.1937	.985		
2.450	.1957	.989		1
2.475	.1977	.993		
2.500	.1997	.997		1
2.525	.2017	.999		
2.550	.2037	1.001		1
2.575	.2057	1.003		
2.600	.2077	1.005		1
2.625	.2097	1.007		
2.650	.2117	1.009		1
2.675	.2137	1.011		
2.700	.2157	1.013		1
2.725	.2177	1.015		
2.750	.2197	1.017		1
2.775	.2217	1.019		
2.800	.2237	1.021		1
2.825	.2257	1.023		
2.850	.2277	1.025		1
2.875	.2297	1.027		
2.900	.2317	1.029		1
2.925	.2337	1.031		
2.950	.2357	1.033		1
2.975	.2377	1.035		
3.000	.2397	1.037		1
3.025	.2417	1.039		
3.050	.2437	1.041		1
3.075	.2457	1.043		
3.100	.2477	1.045		1
3.125	.2497	1.047		
3.150	.2517	1.049		1
3.175	.2537	1.051		
3.200	.2557	1.053		1
3.225	.2577	1.055		
3.250	.2597	1.057		1
3.275	.2617	1.059		
3.300	.2637	1.061		1
3.325	.2657	1.063		
3.350	.2677	1.065		1
3.375	.2697	1.067		
3.400	.2717	1.069		1
3.425	.2737	1.071		
3.450	.2757	1.073		1
3.475	.2777	1.075		
3.500	.2797	1.077		1
3.525	.2817	1.079		
3.550	.2837	1.081		1
3.575	.2857	1.083		
3.600	.2877	1.085		1
3.625	.2897	1.087		
3.650	.2917	1.089		1
3.675	.2937	1.091		
3.700	.2957	1.093		1
3.725	.2977	1.095		
3.750	.2997	1.097		1
3.775	.3017	1.099		
3.800	.3037	1.101		1
3.825	.3057	1.103		
3.850	.3077	1.105		1
3.875	.3097	1.107		
3.900	.3117	1.109		1
3.925	.3137	1.111		
3.950	.3157	1.113		1
3.975	.3177	1.115		
4.000	.3197	1.117		1
4.025	.3217	1.119		
4.050	.3237	1.121		1
4.075	.3257	1.123		
4.100	.3277	1.125		1
4.125	.3297	1.127		
4.150	.3317	1.129		1
4.175	.3337	1.131		
4.200	.3357	1.133		1
4.225	.3377	1.135		
4.250	.3397	1.137		1
4.275	.3417	1.139		
4.300	.3437	1.141		1
4.325	.3457	1.143		
4.350	.3477	1.145		1
4.375	.3497	1.147		
4.400	.3517	1.149		1
4.425	.3537	1.151		
4.450	.3557	1.153		1
4.475	.3577	1.155		
4.500	.3597	1.157		1
4.525	.3617	1.159		
4.550	.3637	1.161		1
4.575	.3657	1.163		
4.600	.3677	1.165		1
4.625	.3697	1.167		
4.650	.3717	1.169		1
4.675	.3737	1.171		
4.700	.3757	1.173		1
4.725	.3777	1.175		
4.750	.3797	1.177		1
4.775	.3817	1.179		
4.800	.3837	1.181		1
4.825	.3857	1.183		
4.850	.3877	1.185		1
4.875	.3897	1.187		
4.900	.3917	1.189		1
4.925	.3937	1.191		
4.950	.3957	1.193		1
4.975	.3977	1.195		
5.000	.3997	1.197		1
5.025	.4017	1.199		
5.050	.4037	1.201		1
5.075	.4057	1.203		
5.100	.4077	1.205		1
5.125	.4097	1.207		
5.150	.4117	1.209		1
5.175	.4137	1.211		
5.200	.4157	1.213		1
5.225	.4177	1.215		
5.250	.4197	1.217		1
5.275	.4217	1.219		
5.300	.4237	1.221		1
5.325	.4257	1.223		
5.350	.4277	1.225		1
5.375	.4297	1.227		
5.400	.4317	1.229		1
5.425	.4337	1.231		
5.450	.4357	1.233		1
5.475	.4377	1.235		
5.500	.4397	1.237		1
5.525	.4417	1.239		
5.550	.4437	1.241		1
5.575	.4457	1.243		
5.600	.4477	1.245		1
5.625	.4497	1.247		
5.650	.4517	1.249		1
5.675	.4537	1.251		
5.700	.4557	1.253		1
5.725	.4577	1.255		
5.750	.4597	1.257		1
5.775	.4617	1.259		
5.800	.4637	1.261		1
5.825	.4657	1.263		
5.850	.4677	1.265		1
5.875	.4697	1.267		
5.900	.4717	1.269		1
5.925	.4737	1.271		
5.950	.4757	1.273		1
5.975	.4777	1.275		
6.000	.4797	1.277		1
6.025	.4817	1.279		
6.050	.4837	1.281		1
6.075	.4857	1.283		
6.100	.4877	1.285		1
6.125	.4897	1.287		
6.150	.4917	1.289		1
6.175	.4937	1.291		
6.200	.4957	1.293		1
6.225	.4977	1.295		
6.250	.4997	1.297		1
6.275	.5017	1.299		
6.300	.5037	1.301		1
6.325	.5057	1.303		
6.350	.5077	1.305		1
6.375	.5097	1.307		
6.400	.5117	1.309		1
6.425	.5137	1.311		
6.450	.5157	1.313		1
6.475	.5177	1.315		
6.500	.5197	1.317		1
6.525	.5217	1.319		
6.550	.5237	1.321		1
6.575	.5257	1.323		
6.600	.5277	1.325		1
6.625	.5297	1.327		
6.650	.5317	1.329		1
6.675	.5337	1.331		
6.700	.5357	1.333		1
6.725	.5377	1.335		
6.750	.5397	1.337		1
6.775	.5417	1.339		
6.800	.5437	1.341		1
6.825	.5457	1.343		
6.850	.5477	1.345		1
6.875	.5497	1.347		
6.900	.5517	1.349		1
6.925	.5537	1.351		
6.950	.5557	1.353		1
6.975	.5577	1.355		
7.000	.5597	1.357		1
7.025	.5617	1.359		
7.050	.5637	1.361		1
7.075	.5657	1.363		
7.100	.5677	1.365		1
7.125	.5697	1.367		
7.150	.5717	1.369		1
7.175	.5737	1.371		
7.200	.5757	1.373		1
7.225	.5777	1.375		
7.250	.5797	1.377		1
7.275	.5817	1.379		
7.300	.5837	1.381		1
7.325	.5857	1.383		
7.350	.5877	1.385		1
7.375	.5897	1.387		
7.400	.5917	1.389		1
7.425	.5937	1.391		
7.4				

ORIGINAL PAGE IS
OF POOR QUALITY

STATION NO. E14 z = 52.1 cm z = -15.24cm									
$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2} =$									
y, cm	y/d	P/Q _{ref}	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$	$\frac{P_{Q_{ref}} - P_{w_{ref}}}{\rho Q_{ref}^2}$
0	0	.0011	.404						
.022	.0014	.0016							
.037	.0016	.0022							
.052	.0018	.0027							
.067	.0020	.0032							
.082	.0022	.0037							
.097	.0024	.0042							
.112	.0026	.0047							
.127	.0028	.0052							
.142	.0030	.0057							
.157	.0032	.0062							
.172	.0034	.0067							
.187	.0036	.0072							
.202	.0038	.0077							
.217	.0040	.0082							
.232	.0042	.0087							
.247	.0044	.0092							
.262	.0046	.0097							
.277	.0048	.0102							
.292	.0050	.0107							
.307	.0052	.0112							
.322	.0054	.0117							
.337	.0056	.0122							
.352	.0058	.0127							
.367	.0060	.0132							
.382	.0062	.0137							
.397	.0064	.0142							
.412	.0066	.0147							
.427	.0068	.0152							
.442	.0070	.0157							
.457	.0072	.0162							
.472	.0074	.0167							
.487	.0076	.0172							
.502	.0078	.0177							
.517	.0080	.0182							
.532	.0082	.0187							
.547	.0084	.0192							
.562	.0086	.0197							
.577	.0088	.0202							
.592	.0090	.0207							
.607	.0092	.0212							
.622	.0094	.0217							
.637	.0096	.0222							
.652	.0098	.0227							
.667	.0100	.0232							
.682	.0102	.0237							
.697	.0104	.0242							
.712	.0106	.0247							
.727	.0108	.0252							
.742	.0110	.0257							
.757	.0112	.0262							
.772	.0114	.0267							
.787	.0116	.0272							
.802	.0118	.0277							
.817	.0120	.0282							
.832	.0122	.0287							
.847	.0124	.0292							
.862	.0126	.0297							
.877	.0128	.0302							
.892	.0130	.0307							
.907	.0132	.0312							
.922	.0134	.0317							
.937	.0136	.0322							
.952	.0138	.0327							
.967	.0140	.0332							
.982	.0142	.0337							
.997	.0144	.0342							
1.012	.0146	.0347							
1.027	.0148	.0352							
1.042	.0150	.0357							
1.057	.0152	.0362							
1.072	.0154	.0367							
1.087	.0156	.0372							
1.102	.0158	.0377							
1.117	.0160	.0382							
1.132	.0162	.0387							
1.147	.0164	.0392							
1.162	.0166	.0397							
1.177	.0168	.0402							
1.192	.0170	.0407							
1.207	.0172	.0412							
1.222	.0174	.0417							
1.237	.0176	.0422							
1.252	.0178	.0427							
1.267	.0180	.0432							
1.282	.0182	.0437							
1.297	.0184	.0442							
1.312	.0186	.0447							
1.327	.0188	.0452							
1.342	.0190	.0457							
1.357	.0192	.0462							
1.372	.0194	.0467							
1.387	.0196	.0472							
1.402	.0198	.0477							
1.417	.0200	.0482							
1.432	.0202	.0487							
1.447	.0204	.0492							
1.462	.0206	.0497							
1.477	.0208	.0502							
1.492	.0210	.0507							
1.507	.0212	.0512							
1.522	.0214	.0517							
1.537	.0216	.0522							
1.552	.0218	.0527							
1.567	.0220	.0532							
1.582	.0222	.0537							
1.597	.0224	.0542							
1.612	.0226	.0547							
1.627	.0228	.0552							
1.642	.0230	.0557							
1.657	.0232	.0562							
1.672	.0234	.0567							
1.687	.0236	.0572							
1.702	.0238	.0577							
1.717	.0240	.0582							
1.732	.0242	.0587							
1.747	.0244	.0592							
1.762	.0246	.0597							
1.777	.0248	.0602							
1.792	.0250	.0607							
1.807	.0252	.0612							
1.822	.0254	.0617							
1.837	.0256	.0622							
1.852	.0258	.0627							
1.867	.0260	.0632							
1.882	.0262	.0637							
1.897	.0264	.0642							
1.912	.0266	.0647							
1.927	.0268	.0652							
1.942	.0270	.0657							
1.957	.0272	.0662							
1.972	.0274	.0667							
1.987	.0276	.0672							
2.002	.0278	.0677							
2.017	.0280	.0682							
2.032	.0282	.0687							
2.047	.0284	.0692							
2.062	.0286	.0697							
2.077	.0288	.0702							
2.092	.0290	.0707							
2.107	.0292	.0712							
2.122	.0294	.0717							
2.137	.0296	.0722							
2.152	.0298	.0727							
2.167	.0300	.0732							
2.182	.0302	.0737							
2.197	.0304	.0742							
2.212	.0306	.0747							
2.227	.0308	.0752							
2.242	.0310	.0757							
2.257	.0312	.0762							
2.272	.0314	.0767							
2.287	.0316	.0772							
2.302	.0318	.0777							
2.317	.0320	.0782							
2.332	.0322	.0787							
2.347	.0324	.0792							
2.362	.0326	.0797							
2.377	.0328	.0802							
2.392	.0330	.0807							
2.407	.0332	.0812							
2.422	.0334	.0817							
2.437	.0336	.0822							
2.452	.0338	.0827							
2.467	.0340	.0832							
2.482	.0342	.0837							
2.497	.0344	.0842							
2.512	.0346	.0847							
2.527	.0348	.0852							
2.542	.0350	.0857							
2.557	.0352	.0862							
2.572	.0354	.0867							
2.587	.0356	.0872							
2.602	.0358	.0877							
2.617	.0360	.0882							
2.632	.0362	.0887							
2.647	.0364	.0892							
2.662	.0366	.0897							
2.677	.0368	.0902							
2.692	.0370	.0907							
2.707	.0372	.0912							
2.722	.0374	.0917							
2.737	.0376	.0922							
2.752	.0378	.0927							
2.767	.0380	.0932							
2.782	.0382	.0937							
2.797	.0384	.0942							
2.812	.0386	.0947							
2.827	.0388	.0952							
2.842	.0390	.0957							
2.857	.0392	.0962							
2.872	.0394	.0967							
2.887	.0396	.0972							
2.902	.0398	.0977							
2.917	.0400	.0982							
2.932	.0402	.0987							

STATION NO. E34 z = 140.3 cm z = 15.24 cm					
$\frac{P_w - P_{w,ref}}{Q_{ref}}$ = .25					
y, cm	y/d	P/Q_{ref}	$(P - P_w)/Q_{ref}$	γ_p	
0	0	.0019	.25		
.022	.0022	.0019			
.037	.0037	.0028			
.052	.0052	.0036			
.067	.0067	.0045			
.082	.0082	.0052			
.097	.0097	.0060			
.112	.0112	.0068			
.127	.0127	.0074			
.142	.0142	.0081			
.157	.0157	.0087			
.172	.0172	.0093			
.187	.0187	.0100			
.202	.0202	.0107			
.217	.0217	.0114			
.232	.0232	.0121			
.247	.0247	.0128			
.262	.0262	.0135			
.277	.0277	.0142			
.292	.0292	.0149			
.307	.0307	.0156			
.322	.0322	.0163			
.337	.0337	.0170			
.352	.0352	.0177			
.367	.0367	.0184			
.382	.0382	.0191			
.397	.0397	.0198			
.412	.0412	.0205			
.427	.0427	.0212			
.442	.0442	.0219			
.457	.0457	.0226			
.472	.0472	.0233			
.487	.0487	.0240			
.502	.0502	.0247			
.517	.0517	.0254			
.532	.0532	.0261			
.547	.0547	.0268			
.562	.0562	.0275			
.577	.0577	.0282			
.592	.0592	.0289			
.607	.0607	.0296			
.622	.0622	.0303			
.637	.0637	.0310			
.652	.0652	.0317			
.667	.0667	.0324			
.682	.0682	.0331			
.697	.0697	.0338			
.712	.0712	.0345			
.727	.0727	.0352			
.742	.0742	.0359			
.757	.0757	.0366			
.772	.0772	.0373			
.787	.0787	.0380			
.802	.0802	.0387			
.817	.0817	.0394			
.832	.0832	.0401			
.847	.0847	.0408			
.862	.0862	.0415			
.877	.0877	.0422			
.892	.0892	.0429			
.907	.0907	.0436			
.922	.0922	.0443			
.937	.0937	.0450			
.952	.0952	.0457			
.967	.0967	.0464			
.982	.0982	.0471			
.997	.0997	.0478			
1.012	.1012	.0485			
1.027	.1027	.0492			
1.042	.1042	.0499			
1.057	.1057	.0506			
1.072	.1072	.0513			
1.087	.1087	.0520			
1.102	.1102	.0527			
1.117	.1117	.0534			
1.132	.1132	.0541			
1.147	.1147	.0548			
1.162	.1162	.0555			
1.177	.1177	.0562			
1.192	.1192	.0569			
1.207	.1207	.0576			
1.222	.1222	.0583			
1.237	.1237	.0590			
1.252	.1252	.0597			
1.267	.1267	.0604			
1.282	.1282	.0611			
1.297	.1297	.0618			
1.312	.1312	.0625			
1.327	.1327	.0632			
1.342	.1342	.0639			
1.357	.1357	.0646			
1.372	.1372	.0653			
1.387	.1387	.0660			
1.402	.1402	.0667			
1.417	.1417	.0674			
1.432	.1432	.0681			
1.447	.1447	.0688			
1.462	.1462	.0695			
1.477	.1477	.0702			
1.492	.1492	.0709			
1.507	.1507	.0716			
1.522	.1522	.0723			
1.537	.1537	.0730			
1.552	.1552	.0737			
1.567	.1567	.0744			
1.582	.1582	.0751			
1.597	.1597	.0758			
1.612	.1612	.0765			
1.627	.1627	.0772			
1.642	.1642	.0779			
1.657	.1657	.0786			
1.672	.1672	.0793			
1.687	.1687	.0800			
1.702	.1702	.0807			
1.717	.1717	.0814			
1.732	.1732	.0821			
1.747	.1747	.0828			
1.762	.1762	.0835			
1.777	.1777	.0842			
1.792	.1792	.0849			
1.807	.1807	.0856			
1.822	.1822	.0863			
1.837	.1837	.0870			
1.852	.1852	.0877			
1.867	.1867	.0884			
1.882	.1882	.0891			
1.897	.1897	.0898			
1.912	.1912	.0905			
1.927	.1927	.0912			
1.942	.1942	.0919			
1.957	.1957	.0926			
1.972	.1972	.0933			
1.987	.1987	.0940			
1.002	.1002	.0947			
1.017	.1017	.0954			
1.032	.1032	.0961			
1.047	.1047	.0968			
1.062	.1062	.0975			
1.077	.1077	.0982			
1.092	.1092	.0989			
1.107	.1107	.0996			
1.122	.1122	.1003			
1.137	.1137	.1010			
1.152	.1152	.1017			
1.167	.1167	.1024			
1.182	.1182	.1031			
1.197	.1197	.1038			
1.212	.1212	.1045			
1.227	.1227	.1052			
1.242	.1242	.1059			
1.257	.1257	.1066			
1.272	.1272	.1073			
1.287	.1287	.1080			
1.302	.1302	.1087			
1.317	.1317	.1094			
1.332	.1332	.1101			
1.347	.1347	.1108			
1.362	.1362	.1115			
1.377	.1377	.1122			
1.392	.1392	.1129			
1.407	.1407	.1136			
1.422	.1422	.1143			
1.437	.1437	.1150			
1.452	.1452	.1157			
1.467	.1467	.1164			
1.482	.1482	.1171			
1.497	.1497	.1178			
1.512	.1512	.1185			
1.527	.1527	.1192			
1.542	.1542	.1199			
1.557	.1557	.1206			
1.572	.1572	.1213			
1.587	.1587	.1220			
1.602	.1602	.1227			
1.617	.1617	.1234			
1.632	.1632	.1241			
1.647	.1647	.1248			
1.662	.1662	.1255			
1.677	.1677	.1262			
1.692	.1692	.1269			
1.707	.1707	.1276			
1.722	.1722	.1283			
1.737	.1737	.1290			
1.752	.1752	.1297			
1.767	.1767	.1304			
1.782	.1782	.1311			
1.797	.1797	.1318			
1.812	.1812	.1325			
1.827	.1827	.1332			
1.842	.1842	.1339			
1.857	.1857	.1346			
1.872	.1872	.1353			
1.887	.1887	.1360			
1.902	.1902	.1367			
1.917	.1917	.1374			
1.932	.1932	.1381			
1.947	.1947	.1388			
1.962	.1962	.1395			
1.977	.1977	.1402			
1.992	.1992	.1409			
2.007	.2007	.1416			
2.022	.2022	.1423			
2.037	.2037	.1430			
2.052	.2052	.1437			
2.067	.2067	.1444			
2.082	.2082	.1451			
2.097	.2097	.1458			

ORIGINAL PAGE IS
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STATION NO. W18, x = 67.3 cm z = 15.24 cm					
$\frac{w_w - P_w}{\rho_w \gamma_{rel}} \cdot \frac{1}{Q_{rel}} = .411$					
y, cm	y/d	P/Q _{rel}	$(w - P_w)/Q_{rel}$	7p	
0	0	.411			
.047	.0014	.423			
.123	.0038	.427			
.200	.0076	.430			
.275	.0114	.433			
.350	.0152	.435			
.425	.0190	.437			
.500	.0228	.439			
.575	.0266	.441			
.650	.0304	.443			
.725	.0342	.445			
.800	.0380	.447			
.875	.0418	.449			
.950	.0456	.451			
1.025	.0494	.453			
1.100	.0532	.455			
1.175	.0570	.457			
1.250	.0608	.459			
1.325	.0646	.461			
1.400	.0684	.463			
1.475	.0722	.465			
1.550	.0760	.467			
1.625	.0798	.469			
1.700	.0836	.471			
1.775	.0874	.473			
1.850	.0912	.475			
1.925	.0950	.477			
2.000	.0988	.479			
2.075	.1026	.481			
2.150	.1064	.483			
2.225	.1102	.485			
2.300	.1140	.487			
2.375	.1178	.489			
2.450	.1216	.491			
2.525	.1254	.493			
2.600	.1292	.495			
2.675	.1330	.497			
2.750	.1368	.499			
2.825	.1406	.501			
2.900	.1444	.503			
2.975	.1482	.505			
3.050	.1520	.507			
3.125	.1558	.509			
3.200	.1596	.511			
3.275	.1634	.513			
3.350	.1672	.515			
3.425	.1710	.517			
3.500	.1748	.519			
3.575	.1786	.521			
3.650	.1824	.523			
3.725	.1862	.525			
3.800	.1900	.527			
3.875	.1938	.529			
3.950	.1976	.531			
4.025	.2014	.533			
4.100	.2052	.535			
4.175	.2090	.537			
4.250	.2128	.539			
4.325	.2166	.541			
4.400	.2204	.543			
4.475	.2242	.545			
4.550	.2280	.547			
4.625	.2318	.549			
4.700	.2356	.551			
4.775	.2394	.553			
4.850	.2432	.555			
4.925	.2470	.557			
5.000	.2508	.559			
5.075	.2546	.561			
5.150	.2584	.563			
5.225	.2622	.565			
5.300	.2660	.567			
5.375	.2698	.569			
5.450	.2736	.571			
5.525	.2774	.573			
5.600	.2812	.575			
5.675	.2850	.577			
5.750	.2888	.579			
5.825	.2926	.581			
5.900	.2964	.583			
5.975	.3002	.585			
6.050	.3040	.587			
6.125	.3078	.589			
6.200	.3116	.591			
6.275	.3154	.593			
6.350	.3192	.595			
6.425	.3230	.597			
6.500	.3268	.599			
6.575	.3306	.601			
6.650	.3344	.603			
6.725	.3382	.605			
6.800	.3420	.607			
6.875	.3458	.609			
6.950	.3496	.611			
7.025	.3534	.613			
7.100	.3572	.615			
7.175	.3610	.617			
7.250	.3648	.619			
7.325	.3686	.621			
7.400	.3724	.623			
7.475	.3762	.625			
7.550	.3800	.627			
7.625	.3838	.629			
7.700	.3876	.631			
7.775	.3914	.633			
7.850	.3952	.635			
7.925	.3990	.637			
8.000	.4028	.639			
8.075	.4066	.641			
8.150	.4104	.643			
8.225	.4142	.645			
8.300	.4180	.647			
8.375	.4218	.649			
8.450	.4256	.651			
8.525	.4294	.653			
8.600	.4332	.655			
8.675	.4370	.657			
8.750	.4408	.659			
8.825	.4446	.661			
8.900	.4484	.663			
8.975	.4522	.665			
9.050	.4560	.667			
9.125	.4598	.669			
9.200	.4636	.671			
9.275	.4674	.673			
9.350	.4712	.675			
9.425	.4750	.677			
9.500	.4788	.679			
9.575	.4826	.681			
9.650	.4864	.683			
9.725	.4902	.685			
9.800	.4940	.687			
9.875	.4978	.689			
9.950	.5016	.691			
10.025	.5054	.693			
10.100	.5092	.695			
10.175	.5130	.697			
10.250	.5168	.699			
10.325	.5206	.701			
10.400	.5244	.703			
10.475	.5282	.705			
10.550	.5320	.707			
10.625	.5358	.709			
10.700	.5396	.711			
10.775	.5434	.713			
10.850	.5472	.715			
10.925	.5510	.717			
11.000	.5548	.719			
11.075	.5586	.721			
11.150	.5624	.723			
11.225	.5662	.725			
11.300	.5700	.727			
11.375	.5738	.729			
11.450	.5776	.731			
11.525	.5814	.733			
11.600	.5852	.735			
11.675	.5890	.737			
11.750	.5928	.739			
11.825	.5966	.741			
11.900	.6004	.743			
11.975	.6042	.745			
12.050	.6080	.747			
12.125	.6118	.749			
12.200	.6156	.751			
12.275	.6194	.753			
12.350	.6232	.755			
12.425	.6270	.757			
12.500	.6308	.759			
12.575	.6346	.761			
12.650	.6384	.763			
12.725	.6422	.765			
12.800	.6460	.767			
12.875	.6498	.769			
12.950	.6536	.771			
13.025	.6574	.773			
13.100	.6612	.775			
13.175	.6650	.777			
13.250	.6688	.779			
13.325	.6726	.781			
13.400	.6764	.783			
13.475	.6802	.785			
13.550	.6840	.787			
13.625	.6878	.789			
13.700	.6916	.791			
13.775	.6954	.793			
13.850	.6992	.795			
13.925	.7030	.797			
14.000	.7068	.799			
14.075	.7106	.801			
14.150	.7144	.803			
14.225	.7182	.805			
14.300	.7220	.807			
14.375	.7258	.809			
14.450	.7296	.811			
14.525	.7334	.813			
14.600	.7372	.815			
14.675	.7410	.817			
14.750	.7448	.819			
14.825	.7486	.821			
14.900	.7524	.823			
14.975	.7562	.825			
15.050	.7600	.827			
15.125	.7638	.829			
15.200	.7676	.831			
15.275	.7714	.833			
15.350	.7752	.835			
15.425	.7790	.837			
15.500	.7828	.839			
15.575	.7866	.841			
15.650	.7904	.843			
15.725	.7942	.845			
15.800	.7980	.847			
15.875	.8018	.849			
15.950	.8056	.851			
16.025	.8094	.853			
16.100	.8132	.855			
16.175	.8170	.857			
16.250	.8208	.859			
16.325	.8246	.861			
16.400	.8284	.863			
16.475	.8322	.865			
16.550	.8360	.867			
16.625	.8398	.869			
16.700	.8436	.871			
16.775	.8474	.873			
16.850	.8512	.875			
16.925	.8550	.877			
17.000	.8588	.879			
17.075	.8626	.881			
17.150	.8664	.883			
17.225	.8702	.885			
17.300	.8740	.887			
17.375	.8778	.889			
17.450	.8816	.891			
17.525	.8854	.893			
17.600	.8892	.895			
17.675	.8930	.897			
17.750	.8968	.899			
17.825	.9006	.901			
17.900	.9044	.903			
17.975	.9082	.905			
18.050	.9120	.907			
18.125	.9158	.909			
18.200	.9196	.911			
18.275	.9234	.913			
18.350	.9272	.915			
18.425	.9310	.917			
18.500	.9348	.919			
18.575	.9386	.921			
18.650	.9424	.923			
18.725	.9462	.925			
18.800	.9500	.927			
18.875	.9538	.929			
18.950	.9576	.931			
19.025	.9614	.933			
19.100	.9652	.935			
19.175	.9690	.937			
19.250	.9728	.939			
19.325	.9766	.941			
19.400	.9804	.943			
19.475	.9842	.945			
19.550	.9880	.947			
19.625	.9918	.949			
19.700	.9956	.951			
19.775	.9994	.953			
19.850	1.0032	.955			
19.925	1.0070	.957			
20.000	1.0108	.959			
20.075	1.0146	.961			
20.150	1.0184	.963			
20.225	1.0222	.965			
20.300	1.0260	.967			
20.375	1.0298	.969			
20.450	1.0336	.971			
20.525	1.0374	.973			
20.600	1.0412	.975			
20.675	1.0450	.977			
20.750	1.0488	.979			
20.825	1.0526	.981			
20.900	1.0564	.983			
20.975	1.0602	.985			
21.050</					

STATION NO <u>C1</u> $x = 2.54$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
127	.013	.587	.072
203	.020	.426	.071
305	.030	.456	.072
406	.041	.478	.073
508	.051	.495	.072
635	.064	.709	.072
762	.076	.728	.07
1.02	.102	.754	.067
1.27	.127	.777	.064
1.52	.152	.795	.062
2.03	.203	.831	.055
2.54	.254	.863	.051
3.05	.305	.891	.045
3.56	.356	.914	.039
4.06	.407	.935	.034
4.57	.457	.95	.028
5.08	.508	.962	.021
6.35	.635	.978	.011
7.62	.762	.98	.008
8.89	.889	.984	.007
10.16	1.02	.984	.007
12.7	1.27	.986	.006
15.24	1.52	.99	.007
17.78	1.78	.967	.038
20.07	2.01	.804	.06

STATION NO <u>C2</u> $x = 7.6$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
127	.013	.559	.074
203	.021	.594	.074
305	.032	.642	.074
406	.042	.662	.074
508	.053	.685	.073
635	.066	.699	.073
762	.079	.716	.072
1.02	.105	.74	.07
1.27	.131	.764	.067
1.52	.158	.785	.064
2.03	.210	.828	.057
2.54	.263	.862	.052
3.05	.315	.885	.047
3.56	.368	.914	.041
4.06	.420	.937	.035
4.57	.473	.951	.029
5.08	.525	.965	.023
6.35	.656	.982	.012
7.62	.788	.988	.008
8.89	.919	.99	.01
10.16	1.05	.991	.007
12.7	1.31	.995	.007
15.24	1.58	1.001	.007
17.78	1.84	.987	.031
19.939	2.06	.836	.058

STATION NO <u>C3</u> $x = 13.3$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
127	.013	.546	.075
203	.021	.587	.074
305	.031	.623	.074
406	.042	.646	.074
508	.052	.659	.074
635	.065	.68	.073
762	.078	.696	.072
1.02	.104	.722	.069
1.27	.130	.745	.067
1.52	.156	.766	.065
2.03	.208	.801	.059
2.54	.260	.832	.052
3.05	.312	.862	.047
3.56	.364	.886	.042
4.06	.416	.909	.034
4.57	.468	.928	.031
5.08	.520	.941	.024
6.35	.650	.961	.012
7.62	.780	.968	.009
8.89	.911	.973	.008
10.16	1.04	.977	.007
12.7	1.30	.985	.007
15.24	1.56	.986	.007
17.78	1.82	.981	.031
20.07	2.06	.826	.058

STATION NO <u>C5</u> $x = 24.1$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
127	.013	.434	.083
203	.021	.478	.085
305	.031	.506	.086
406	.041	.541	.085
508	.051	.562	.084
635	.064	.582	.085
762	.077	.602	.083
1.02	.103	.631	.079
1.27	.128	.66	.079
1.52	.154	.679	.073
2.03	.205	.72	.068
2.54	.254	.754	.062
3.05	.308	.789	.055
3.56	.359	.818	.049
4.06	.410	.844	.042
4.57	.462	.867	.036
5.08	.513	.887	.03
6.35	.641	.921	.018
7.62	.769	.938	.01
8.89	.898	.951	.008
10.16	1.03	.964	.008
12.7	1.28	.992	.008
15.24	1.54	1.026	.009
17.78	1.80	1.073	.033
20.07	2.03	.954	.055

STATION NO <u>C6</u> $x = 26.7$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
127	.013	.409	.084
203	.020	.427	.089
305	.030	.464	.09
406	.041	.491	.09
508	.051	.517	.089
635	.063	.533	.089
762	.076	.552	.087
1.02	.101	.588	.083
1.27	.127	.611	.08
1.52	.152	.634	.077
2.03	.203	.676	.07
2.54	.253	.713	.065
3.05	.304	.746	.059
3.56	.355	.778	.052
4.06	.405	.803	.045
4.57	.456	.825	.039
5.08	.507	.847	.033
6.35	.634	.888	.02
7.62	.760	.907	.012
8.89	.887	.923	.007
10.16	1.01	.938	.008
12.7	1.27	.97	.007
15.24	1.52	1.014	.008
17.78	1.77	1.096	.019
20.32	2.03	1.018	.055

STATION NO <u>C8</u> $x = 31.8$ cm $z = 0$ cm			
y cm	y/δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
203	.019	.316	.101
305	.028	.333	.108
406	.037	.36	.11
508	.046	.378	.113
635	.058	.404	.112
762	.070	.438	.11
1.02	.093	.474	.106
1.27	.116	.504	.103
1.52	.139	.535	.097
2.03	.185	.584	.089
2.54	.232	.632	.081
3.05	.278	.659	.075
3.56	.324	.705	.066
4.06	.371	.737	.059
4.57	.417	.761	.052
5.08	.463	.789	.045
6.35	.579	.837	.028
7.62	.695	.864	.017
8.89	.811	.889	.011
10.16	.927	.914	.007
12.7	1.16	.93	.008
15.24	1.39	.979	.008
17.78	1.62	1.035	.008
20.32	1.85	1.053	.041

TABLE V HOT-FILM TRAVERSE DATA

ORIGINAL PAGE IS
OF POOR QUALITY

STATION NO. C9 x = 34.3 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.011	.196	.093
203	.018	.217	.101
305	.027	.249	.11
406	.036	.27	.111
508	.045	.29	.114
635	.057	.318	.118
762	.068	.341	.119
1 02	.090	.382	.123
1 27	.113	.417	.118
1 52	.136	.455	.113
2 03	.181	.507	.102
2 54	.226	.556	.091
3 05	.271	.601	.081
3 56	.317	.637	.074
4 06	.362	.675	.066
4 57	.407	.71	.06
5 08	.452	.738	.052
6 35	.545	.791	.036
7 62	.679	.833	.021
8 89	.792	.859	.011
10 16	.905	.878	.008
12 7	1.13	.916	.007
15 24	1.36	.948	.007
17 78	1.58	.992	.007
20 32	1.81	1.018	.024
22 86	2.04	.886	.052

STATION NO. C11 x = 40.6 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.010	.117	.063
203	.015	.126	.067
305	.023	.136	.072
406	.030	.147	.078
508	.038	.152	.082
635	.048	.166	.09
762	.057	.177	.095
1 02	.076	.201	.108
1 27	.095	.235	.114
1 52	.114	.261	.125
2 03	.152	.323	.133
2 54	.191	.378	.138
3 05	.229	.441	.129
3 56	.267	.486	.122
4 06	.305	.524	.103
4 57	.343	.57	.103
5 08	.381	.611	.07
6 35	.474	.684	.07
7 62	.572	.742	.07
8 89	.667	.798	.034
10 16	.762	.824	.026
12 7	.953	.866	.008
15 24	1.14	.893	.007
17 78	1.33	.921	.006
20 32	1.52	.948	.007
22 86	1.71	.967	.02
25 4	1.91	.857	.045

STATION NO. C13 x = 48.3 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.007	.097*	.049*
203	.012	.109*	.054*
305	.017	.112*	.057*
406	.023	.122*	.057*
508	.029	.123*	.055*
635	.036	.123*	.056*
762	.043	.129*	.055*
1 02	.058	.132*	.058*
1 27	.072	.136*	.059*
1 52	.086	.141*	.043*
2 03	.115	.153*	.072*
2 54	.144	.169*	.082*
3 05	.173	.192*	.093*
3 56	.201	.217*	.103*
4 06	.230	.25*	.112*
4 57	.259	.284*	.119*
5 08	.288	.315*	.119*
6 35	.359	.358	.143
7 62	.431	.386*	.119*
8 89	.503	.467	.136
10 16	.575	.46*	.115*
12 7	.719	.554	.121
15 24	.863	.527*	.106*
17 78	1.01	.629	.099
20 32	1.15	.582*	.106*
22 86	1.29	.7	.071
25 4	1.44	.785	.026
27 94	1.58	.818	.011
30 48	1.73	.839	.009
		.864	.009
		.895	.008
		.935	.009
		.969	.028
		.902	.04

STATION NO. C14 x = 52.1 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.007	.094*	.05*
203	.010	.105*	.052*
305	.016	.113*	.053*
406	.021	.115*	.051*
508	.026	.12*	.053*
635	.033	.126*	.054*
762	.039	.13*	.054*
1 02	.052	.131*	.055*
1 27	.066	.133*	.057*
1 52	.079	.136*	.057*
2 03	.105	.139*	.042*
2 54	.131	.146*	.066*
3 05	.157	.157*	.074*
3 56	.184	.169*	.083*
4 06	.210	.184*	.09*
4 57	.236	.214*	.1*
5 08	.262	.228*	.109*
6 35	.328	.263	.133
7 62	.393	.29*	.119*
8 89	.459	.338	.15
10 16	.525	.367*	.122*
12 7	.656	.427	.148
15 24	.787	.43*	.123*
17 78	.918	.515	.141
20 32	1.05	.599	.123
22 86	1.18	.728	.072
25 4	1.31	.804	.029
27 94	1.44	.827	.017
30 48	1.73	.843	.012
		.863	.012
		.903	.012
		.981	.011
		.902	.04

STATION NO. C15 x = 55.9 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.006	.102*	.052*
203	.009	.11*	.054*
305	.014	.12*	.056*
406	.018	.124*	.057*
508	.023	.129*	.057*
635	.029	.132*	.057*
762	.034	.136*	.058*
1 02	.046	.14*	.058*
1 27	.057	.141*	.059*
1 52	.069	.142*	.058*
2 03	.091	.145*	.06*
2 54	.114	.147*	.06*
3 05	.137	.146*	.043*
3 56	.160	.148*	.066*
4 06	.183	.155*	.074*
4 57	.206	.164*	.079*
5 08	.228	.179*	.088*
6 35	.286	.198	.106
7 62	.343	.22*	.109*
8 89	.400	.238	.13
10 16	.457	.275*	.123*
12 7	.571	.301	.145
15 24	.685	.336*	.128*
17 78	.800	.373	.154
20 32	.914	.398*	.13*
22 86	1.03	.444	.155
25 4	1.14	.608	.13
27 94	1.26	.724	.083
30 48	1.37	.800	.043
		.78	.028
		.796	.012
		.803	.012
		.803	.012
		.806	.011
		.895	.013

STATION NO. C16 x = 59.7 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.005	.109*	.054*
203	.008	.12*	.057*
305	.012	.126*	.057*
406	.016	.131*	.056*
508	.020	.135*	.058*
635	.026	.14*	.058*
762	.031	.143*	.059*
1 02	.041	.15*	.059*
1 27	.051	.15*	.059*
1 52	.061	.15*	.058*
2 03	.082	.15*	.059*
2 54	.102	.148*	.059*
3 05	.122	.147*	.061*
3 56	.143	.146*	.062*
4 06	.163	.146*	.063*
4 57	.184	.147*	.067*
5 08	.204	.15*	.071*
6 35	.255	.146	.075
7 62	.306	.173*	.087*
8 89	.357	.18	.094
10 16	.408	.204*	.105*
12 7	.510	.22	.115
15 24	.612	.245*	.119*
17 78	.714	.277	.134
20 32	.816	.314*	.131*
22 86	.918	.338	.148
25 4	1.02	.463	.15
27 94	1.12	.585	.129
30 48	1.22	.674	.084
33 02	1.33	.715	.046
		.706	.025
		.67	.02
		.61	.015
		.514	.014
		.427	.015

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

STATION NO C17 x = 63.5 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.106*	.051*
203	.007	-.121*	.056*
305	.011	-.132*	.058*
406	.014	-.138*	.058*
508	.018	-.14 *	.058*
635	.022	-.152*	.058*
762	.026	-.148*	.061*
1 02	.035	-.154*	.059*
1 27	.044	-.155*	.057*
1 52	.053	-.159*	.058*
2 03	.071	-.152*	.058*
2 54	.088	-.149*	.06 *
3 05	.106	-.146*	.056*
3 56	.124	-.146*	.059*
4 06	.141	-.14 *	.058*
4 57	.159	-.139*	.06 *
5 08	.176	-.139*	.061*
		.131	.062
6 35	.221	-.14 *	.066*
		.141	.071
7 62	.265	-.163*	.082*
		.163	.087
8 89	.309	-.191*	.099*
		.191	.105
10 16	.353	-.228*	.112*
		.238	.123
12 7	.441	.347	.151
15 24	.529	.448	.152
17 78	.618	.553	.142
20 32	.706	.551	.102
22 86	.794	.636	.058
25 4	.882	.661	.04
27 94	.971	.639	.02
30 48	1.06	.59	.015
33 02	1.15	.535	.015

STATION NO C18 x = 67.3 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.136*	.042*
203	.007	-.15 *	.045*
305	.010	-.164*	.047*
406	.013	-.171*	.047*
508	.016	-.175*	.048*
635	.020	-.177*	.047*
762	.024	-.18 *	.048*
1 02	.033	-.186*	.047*
1 27	.041	-.185*	.046*
1 52	.049	-.184*	.046*
2 03	.065	-.178*	.045*
2 54	.082	-.171*	.045*
3 05	.098	-.167*	.045*
3 56	.114	-.164*	.046*
4 06	.131	-.158*	.046*
4 57	.147	-.155*	.046*
5 08	.163	-.148*	.043*
		.135	.06
6 35	.204	-.144*	.045*
		.135	.063
7 62	.245	-.147*	.048*
		.144	.073
8 89	.286	-.159*	.078*
		.159	.086
10 16	.324	-.177*	.092*
		.184	.104
12 7	.408	.275	.139
15 24	.489	.375	.157
17 78	.571	.477	.154
20 32	.653	.569	.137
22 86	.734	.624	.1
25 4	.814	.639	.054
27 94	.897	.61	.036
30 48	.979	.564	.031
33 02	1.04	.53	.029

STATION NO C19 x = 71.1 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.154*	.043*
203	.006	-.166*	.044*
305	.010	-.17 *	.048*
406	.013	-.18 *	.047*
508	.016	-.184*	.049*
635	.020	-.187*	.047*
762	.024	-.184*	.044*
1 02	.032	-.188*	.045*
1 27	.040	-.18 *	.042*
1 52	.048	-.183*	.046*
2 03	.064	-.178*	.044*
2 54	.079	-.175*	.044*
3 05	.095	-.166*	.044*
3 56	.111	-.163*	.044*
4 06	.127	-.158*	.043*
4 57	.143	-.153*	.047*
5 08	.159	-.148*	.044*
		.139	.061
6 35	.199	-.143*	.045*
		.136	.061
7 62	.238	-.137*	.042*
		.134	.063
8 89	.278	-.141*	.044*
		.144	.07
10 16	.318	-.152*	.074*
		.16	.083
12 7	.397	.211	.11
15 24	.477	.302	.144
17 78	.556	.407	.151
20 32	.636	.495	.143
22 86	.715	.581	.11
25 4	.794	.611	.064
27 94	.874	.594	.032
30 48	.953	.55	.024
33 02	1.03	.505	.019

STATION NO C20 x = 74.9 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.157*	.047*
203	.006	-.184*	.07 *
305	.009	-.189*	.069*
406	.012	-.197*	.071*
508	.015	-.201*	.071*
635	.019	-.202*	.069*
762	.023	-.202*	.07 *
1 02	.030	-.207*	.068*
1 27	.038	-.205*	.069*
1 52	.045	-.2 *	.068*
2 03	.060	-.19 *	.069*
2 54	.075	-.184*	.067*
3 05	.090	-.181*	.068*
3 56	.105	-.173*	.068*
4 06	.120	-.167*	.071*
4 57	.135	-.164*	.069*
5 08	.151	-.156*	.067*
		.151	.067
6 35	.188	-.15 *	.066*
		.147	.066
7 62	.226	-.145*	.068*
		.141	.065
8 89	.263	-.142*	.045*
		.141	.048
10 16	.301	-.145*	.047*
		.147	.072
12 7	.376	.174	.098
15 24	.452	.25	.134
17 78	.527	.35	.148
20 32	.602	.46	.145
22 86	.677	.544	.115
25 4	.753	.612	.074
27 94	.828	.617	.041
30 48	.903	.588	.032
33 02	.978	.548	.029

STATION NO C21 x = 78.7 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.186*	.074*
203	.006	-.203*	.076*
305	.010	-.212*	.075*
406	.013	-.218*	.077*
508	.016	-.222*	.076*
635	.020	-.224*	.074*
762	.024	-.224*	.074*
1 02	.032	-.221*	.072*
1 27	.040	-.219*	.073*
1 52	.048	-.213*	.073*
2 03	.064	-.208*	.073*
2 54	.079	-.202*	.073*
3 05	.095	-.192*	.073*
3 56	.111	-.186*	.073*
4 06	.127	-.184*	.075*
4 57	.143	-.179*	.075*
5 08	.159	-.172*	.074*
		.155	.068
6 35	.199	-.166*	.074*
		.152	.069
7 62	.238	-.157*	.072*
		.143	.065
8 89	.278	-.153*	.071*
		.142	.044
10 16	.318	-.148*	.049*
		.145	.069
12 7	.397	.144	.084
15 24	.477	.227	.115
17 78	.556	.345	.133
20 32	.636	.45	.127
22 86	.715	.549	.102
25 4	.795	.609	.06
27 94	.874	.604	.028
30 48	.954	.567	.023
33 02	1.03	.53	.02

STATION NO C22 x = 82.6 cm z = 0 cm			
y cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
127	.004	-.204*	.079*
203	.006	-.218*	.081*
305	.009	-.227*	.08 *
406	.013	-.232*	.079*
508	.016	-.231*	.078*
635	.020	-.232*	.077*
762	.024	-.23 *	.076*
1 02	.031	-.228*	.074*
1 27	.039	-.228*	.075*
1 52	.047	-.222*	.075*
2 03	.063	-.213*	.074*
2 54	.079	-.204*	.075*
3 05	.094	-.199*	.076*
3 56	.110	-.194*	.077*
4 06	.126	-.187*	.077*
4 57	.142	-.182*	.077*
5 08	.157	-.179*	.077*
		.165	.073
6 35	.197	-.169*	.076*
		.158	.072
7 62	.236	-.165*	.075*
		.152	.07
8 89	.275	-.156*	.07
		.145	.067
10 16	.314	-.151*	.071*
		.144	.068
12 7	.393	.163	.083
15 24	.472	.232	.107
17 78	.550	.36	.122
20 32	.629	.466	.113
22 86	.708	.571	.089
25 4	.786	.623	.05
27 94	.865	.608	.027
30 48	.943	.568	.02
33 02	1.02	.528	.019

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

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STATION NO C23 x = 86.4 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.004	-.22*	.082*
.203	.006	-.223*	.082*
.305	.010	-.232*	.081*
.406	.013	-.226*	.077*
.508	.016	-.227*	.078*
.635	.020	-.23*	.074*
.762	.024	-.223*	.074*
1.02	.032	-.218*	.072*
1.27	.040	-.219*	.075*
1.52	.048	-.214*	.075*
2.03	.064	-.201*	.072*
2.54	.080	-.198*	.072*
3.05	.096	-.195*	.074*
3.56	.112	-.183*	.074*
4.06	.128	-.183*	.075*
4.57	.144	-.184*	.077*
5.08	.159	-.174*	.077*
		.169	.075
6.35	.199	-.171*	.074*
		.164	.075
7.62	.239	-.161*	.075*
		.156	.071
8.89	.279	-.153*	.073*
		.154	.072
10.16	.319	-.147*	.072*
		.151	.071
12.7	.399	.174	.087
15.24	.478	.267	.108
17.78	.558	.395	.111
20.32	.638	.514	.096
22.86	.718	.612	.069
25.4	.797	.642	.035
27.94	.877	.613	.024
30.48	.957	.569	.022
33.02	1.04	.519	.018

STATION NO C24 x = 90.2 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.004	-.218*	.085*
.203	.007	-.225*	.084*
.305	.010	-.232*	.083*
.406	.014	-.228*	.081*
.508	.017	-.23*	.081*
.635	.022	-.228*	.081*
.762	.026	-.22*	.078*
1.02	.035	-.225*	.078*
1.27	.043	-.216*	.076*
1.52	.052	-.212*	.076*
2.03	.069	-.208*	.077*
2.54	.087	-.201*	.078*
3.05	.104	-.198*	.079*
3.56	.121	-.193*	.079*
4.06	.139	-.19*	.079*
4.57	.156	-.183*	.079*
5.08	.173	-.182*	.079*
		.179	.081
6.35	.217	-.172*	.078*
		.179	.084
7.62	.260	-.166*	.078*
		.165	.079
8.89	.303	-.162*	.079*
		.160	.082
10.16	.347	-.162*	.079*
		.17	.083
12.7	.433	.222	.103
15.24	.520	.356	.116
17.78	.607	.48	.103
20.32	.693	.607	.078
22.86	.780	.672	.044
25.4	.867	.669	.026
27.94	.953	.635	.022
30.48	1.04	.594	.02
33.02	1.13	.546	.018

STATION NO C25 x = 94.0 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.005	-.204*	.086*
.203	.008	-.195	.084
.305	.012	-.217*	.091*
.406	.016	-.201	.081
.508	.020	-.215*	.083*
.635	.025	-.199	.078
.762	.030	-.215*	.081*
1.02	.040	-.198	.077
1.27	.049	-.213*	.08*
1.52	.059	-.194	.074
2.03	.079	-.215*	.08*
2.54	.099	-.197	.075
3.05	.119	-.21*	.079*
3.56	.138	-.195	.074
4.06	.158	-.203*	.076*
4.57	.178	-.194	.073
5.08	.198	-.199*	.077*
6.35	.247	-.189	.074
7.62	.297	-.195*	.078*
8.89	.346	-.193	.074
10.16	.395	-.2*	.081*
12.7	.494	-.187	.075
15.24	.593	-.189	.082*
17.78	.692	-.197*	.082*
20.32	.791	-.191	.079
22.86	.890	-.194*	.083*
25.4	.988	-.187	.08
27.94	1.09	-.191*	.084*
30.48	1.19	-.185	.08
		-.186*	.084*
		-.183	.082
		-.182	.084
		-.187*	.075*
		-.188	.091
		-.201*	.104*
		.209	.104
		.31	.122
		.439	.112
		.573	.091
		.704	.056
		.833	.029
		.964	.023
		.109	.021
		.62	.019

STATION NO C26 x = 97.8 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.005	.163	.074
.203	.008	.167	.073
.305	.013	.168	.069
.406	.017	.168	.069
.508	.021	.17	.068
.635	.026	.169	.067
.762	.032	.17	.068
1.02	.042	.174	.068
1.27	.053	.174	.07
1.52	.064	.177	.071
2.03	.085	.182	.075
2.54	.106	.186	.079
3.05	.127	.188	.082
3.56	.148	.19	.086
4.06	.170	.191	.088
4.57	.191	.193	.09
5.08	.212	.195	.093
6.35	.265	.204	.102
7.62	.318	.217	.109
8.89	.371	.249	.124
10.16	.424	.289	.132
12.7	.530	.419	.132
15.24	.636	.567	.103
17.78	.742	.69	.07
20.32	.848	.744	.033
22.86	.954	.743	.025
25.4	1.04	.724	.021
27.94	1.17	.703	.02

STATION NO C28 x = 105.4 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.004	.118	.054
.203	.010	.124	.058
.305	.015	.13	.059
.406	.020	.137	.061
.508	.025	.14	.061
.635	.032	.146	.064
.762	.038	.151	.064
1.02	.051	.164	.072
1.27	.064	.169	.074
1.52	.074	.179	.081
2.03	.102	.191	.089
2.54	.127	.203	.095
3.05	.153	.214	.103
3.56	.178	.223	.109
4.06	.204	.232	.114
4.57	.229	.239	.117
5.08	.254	.251	.123
6.35	.318	.281	.135
7.62	.382	.329	.142
8.89	.445	.391	.143
10.16	.509	.463	.137
12.7	.636	.629	.095
15.24	.763	.73	.053
17.78	.890	.771	.028
20.32	1.02	.77	.023
22.86	1.14	.763	.02

STATION NO C30 x = 113.0 cm z = 0 cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.008	.268	.095
.203	.012	.283	.097
.305	.019	.295	.095
.406	.025	.301	.094
.508	.031	.308	.095
.635	.039	.314	.095
.762	.046	.322	.095
1.02	.062	.336	.097
1.27	.077	.344	.1
1.52	.093	.351	.102
2.03	.124	.364	.108
2.54	.155	.38	.111
3.05	.186	.391	.118
3.56	.216	.405	.122
4.06	.247	.415	.125
4.57	.278	.431	.128
5.08	.309	.449	.132
6.35	.387	.493	.137
7.62	.464	.568	.133
8.89	.541	.649	.114
10.16	.619	.724	.086
12.7	.773	.822	.037
15.24	.928	.855	.028
17.78	1.08	.863	.026

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

STATION NO. E2 $x = 7.6 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.014	.578	.073
2.03	.022	.61	.074
3.05	.033	.643	.074
4.06	.044	.665	.074
5.08	.055	.685	.073
6.35	.069	.702	.072
7.62	.083	.719	.071
1.02	.111	.744	.069
1.27	.139	.772	.066
1.52	.166	.793	.063
2.03	.222	.831	.056
2.54	.277	.865	.051
3.05	.332	.897	.046
3.56	.388	.923	.04
4.06	.443	.946	.033
4.57	.499	.962	.027
5.08	.554	.974	.021
6.35	.693	.989	.011
7.62	.831	.993	.009
8.89	.970	.997	.012
10.16	1.11	1.001	.007
12.7	1.39	1.006	.007
15.24	1.66	1.009	.007
17.78	1.94	.991	.038
20.07	2.19	.811	.06

STATION NO. E6 $x = 24.7 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.013	.359	.088
2.03	.020	.4	.092
3.05	.030	.432	.094
4.06	.041	.463	.094
5.08	.051	.48	.094
6.35	.063	.51	.093
7.62	.076	.532	.092
1.02	.101	.569	.086
1.27	.127	.594	.083
1.52	.152	.619	.08
2.03	.203	.661	.073
2.54	.253	.698	.068
3.05	.304	.732	.063
3.56	.355	.764	.057
4.06	.405	.792	.051
4.57	.456	.815	.045
5.08	.507	.836	.039
6.35	.634	.884	.028
7.62	.740	.914	.017
8.89	.887	.935	.011
10.16	1.01	.95	.009
12.7	1.27	.984	.008
15.24	1.52	1.036	.009
17.78	1.77	1.093	.017
20.07	2.00	1.049	.052

STATION NO. E11 $x = 40.6 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.010	.111	.055
2.03	.015	.118	.059
3.05	.023	.125	.062
4.06	.030	.13	.064
5.08	.038	.139	.071
6.35	.048	.149	.076
7.62	.057	.162	.085
1.02	.076	.183	.098
1.27	.095	.209	.109
1.52	.114	.232	.116
2.03	.152	.286	.131
2.54	.191	.343	.135
3.05	.229	.392	.134
3.57	.267	.443	.124
4.06	.305	.47	.12
4.57	.343	.533	.106
5.08	.381	.568	.098
6.35	.476	.651	.072
7.62	.572	.715	.053
8.89	.667	.765	.038
10.16	.762	.805	.023
12.7	.953	.847	.008
15.24	1.14	.875	.007
17.78	1.33	.904	.004
20.32	1.52	.933	.007
22.86	1.71	.947	.019
25.4	1.91	.832	.044

STATION NO. E18 $x = 67.3 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.004	.13	.043
2.03	.007	.139	.042
3.05	.010	.149	.043
4.06	.014	.157	.045
5.08	.017	.162	.046
6.35	.022	.163	.045
7.62	.024	.164	.045
1.02	.035	.167	.045
1.27	.044	.167	.044
1.52	.052	.166	.043
2.03	.070	.162	.044
2.54	.087	.156	.044
3.05	.105	.148	.043
3.56	.122	.143	.044
4.06	.140	.138	.043
4.57	.157	.133	.041
5.08	.174	.129	.041
6.35	.218	.122	.057
7.62	.262	.126	.06
8.89	.305	.123	.06
10.16	.349	.13	.065
12.7	.436	.131	.066
15.24	.525	.144	.073
17.78	.615	.147	.079
20.32	.698	.175	.099
22.86	.785	.239	.131
25.4	.873	.338	.151
27.94	.959	.434	.156
30.48	1.05	.519	.145
33.02	1.13	.597	.108
		.623	.044
		.604	.035
		.561	.029
		.521	.018

STATION NO. E24 $x = 90.2 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.005	.201	.087
2.03	.007	.214	.084
3.05	.011	.224	.085
4.06	.015	.22	.084
5.08	.018	.217	.082
6.35	.023	.215	.08
7.62	.028	.21	.079
1.02	.037	.205	.077
1.27	.044	.197	.074
1.52	.055	.192	.074
2.03	.073	.181	.073
2.54	.092	.173	.071
3.05	.110	.168	.071
3.56	.128	.16	.07
4.06	.147	.161	.072
4.57	.165	.156	.072
5.08	.183	.155	.073
6.35	.229	.116	.073
7.62	.275	.152	.075
8.89	.321	.155	.077
10.16	.367	.166	.086
12.7	.458	.168	.085
15.24	.550	.184	.091
17.78	.642	.189	.093
20.32	.734	.21	.096
22.86	.825	.226	.101
25.4	.917	.307	.107
27.94	1.01	.411	.101
30.48	1.10	.513	.089
33.02	1.19	.61	.071
		.67	.042
		.669	.026
		.642	.022
		.612	.02
		.547	.018

STATION NO. E28 $x = 105.4 \text{ cm } z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
1.27	.004	.121	.058
2.03	.010	.13	.059
3.05	.015	.138	.063
4.06	.020	.142	.062
5.08	.025	.149	.066
6.35	.032	.157	.068
7.62	.038	.165	.072
1.02	.051	.177	.078
1.27	.064	.188	.083
1.52	.076	.203	.091
2.03	.102	.225	.098
2.54	.127	.244	.109
3.05	.153	.267	.112
3.56	.178	.285	.118
4.06	.204	.308	.123
4.57	.229	.333	.127
5.08	.254	.359	.129
6.35	.318	.426	.129
7.62	.382	.478	.123
8.89	.445	.546	.107
10.16	.509	.604	.091
12.7	.636	.698	.059
15.24	.763	.752	.031
17.78	.890	.745	.021
20.32	1.02	.76	.017
22.86	1.14	.752	.017

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

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STATION NO. E31 $x = 119.4 \text{ cm}$ $z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.010	.452	.094
.203	.017	.469	.095
.305	.025	.479	.091
.406	.033	.49	.09
.508	.042	.491	.09
.635	.052	.497	.089
.762	.062	.506	.089
1.02	.083	.513	.09
1.27	.103	.519	.092
1.52	.125	.53	.094
2.03	.166	.544	.094
2.54	.208	.568	.098
3.05	.249	.587	.1
3.56	.291	.603	.103
4.06	.333	.624	.1
4.57	.374	.648	.098
5.08	.416	.67	.094
6.35	.520	.725	.079
7.62	.624	.781	.054
8.89	.728	.823	.039
10.16	.832	.859	.028
12.7	1.04	.928	.021
14.224	1.16	.987	.022

STATION NO. E34 $x = 140.3 \text{ cm}$ $z = -15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.011	.614	.094
.203	.018	.665	.098
.305	.026	.694	.097
.406	.035	.708	.096
.508	.044	.719	.091
.635	.055	.726	.089
.762	.066	.727	.088
1.02	.088	.735	.085
1.27	.110	.738	.085
1.52	.132	.743	.085
2.03	.174	.747	.09
2.54	.220	.753	.09
3.05	.264	.764	.092
3.56	.308	.769	.092
4.06	.352	.778	.093
4.57	.396	.79	.092
5.08	.440	.799	.09
6.35	.550	.831	.074
7.62	.660	.849	.066
8.89	.770	.863	.05
10.16	.880	.871	.035
12.7	1.10	.877	.023
13.97	1.21	.873	.024

STATION NO. W2 $x = 7.6 \text{ cm}$ $z = 15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.014	.547	.075
.203	.022	.585	.075
.305	.033	.621	.075
.406	.044	.646	.074
.508	.054	.667	.074
.635	.068	.684	.073
.762	.082	.703	.072
1.02	.109	.729	.07
1.27	.136	.753	.067
1.52	.163	.774	.064
2.03	.218	.812	.058
2.54	.272	.839	.054
3.05	.326	.868	.049
3.56	.381	.891	.044
4.06	.435	.912	.039
4.57	.489	.934	.035
5.08	.544	.949	.029
6.35	.660	.975	.018
7.62	.816	.984	.009
8.89	.952	.991	.008
10.16	1.09	.991	.008
12.7	1.36	.994	.007
15.24	1.63	1.001	.007
17.78	1.90	1.004	.029
19.94	2.13	.993	.059

STATION NO. W6 $x = 26.7 \text{ cm}$ $z = 15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.013	.397	.084
.203	.020	.429	.089
.305	.030	.464	.091
.406	.041	.49	.09
.508	.051	.512	.09
.635	.063	.534	.087
.762	.076	.555	.087
1.02	.101	.591	.083
1.27	.127	.616	.081
1.52	.152	.64	.074
2.03	.203	.686	.071
2.54	.253	.729	.064
3.05	.304	.761	.059
3.56	.355	.795	.052
4.06	.405	.823	.044
4.57	.456	.847	.038
5.08	.507	.867	.031
6.35	.634	.906	.019
7.62	.760	.924	.012
8.89	.887	.943	.009
10.16	1.01	.959	.009
12.7	1.27	.992	.008
15.24	1.52	1.057	.01
17.78	1.77	1.102	.017
20.07	2.00	1.035	.056

STATION NO. W11 $x = 40.6 \text{ cm}$ $z = 15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.009	.108	.055
.203	.015	.116	.058
.305	.023	.127	.063
.406	.030	.134	.068
.508	.038	.144	.073
.635	.047	.154	.08
.762	.057	.168	.088
1.02	.075	.19	.1
1.27	.094	.223	.113
1.52	.113	.25	.122
2.03	.151	.309	.131
2.54	.188	.359	.135
3.05	.224	.424	.128
3.56	.264	.474	.119
4.06	.301	.523	.109
4.57	.339	.558	.105
5.08	.377	.603	.088
6.35	.471	.69	.064
7.62	.565	.755	.044
8.89	.659	.799	.024
10.16	.753	.827	.014
12.7	.942	.86	.009
15.24	1.13	.891	.009
17.78	1.32	.921	.008
20.32	1.51	.948	.008
22.86	1.70	.958	.022
25.4	1.88	.83	.044

STATION NO. W18 $x = 67.3 \text{ cm}$ $z = 15.24 \text{ cm}$			
y, cm	y/ δ	U_{eff}/U_{ref}	u_{eff}/U_{ref}
.127	.004	-.138*	.041*
.203	.006	-.152*	.044*
.305	.009	-.16*	.043*
.406	.012	-.165*	.045*
.508	.014	-.171*	.045*
.635	.019	-.17*	.045*
.762	.023	-.169*	.043*
1.02	.031	-.173*	.042*
1.27	.039	-.17*	.04*
1.52	.047	-.174*	.044*
2.03	.061	-.167*	.042*
2.54	.078	-.16*	.043*
3.05	.093	-.155*	.043*
3.56	.109	-.15*	.045*
4.06	.124	-.147*	.043*
4.57	.140	-.142*	.041*
5.08	.155	-.14*	.045*
6.35	.194	.125*	.059
7.62	.233	-.131*	.061*
8.89	.272	-.134*	.062*
10.16	.311	-.145*	.071*
12.7	.388	.147	.079
15.24	.464	-.167*	.088*
17.78	.544	.17	.094
20.32	.621	.256	.131
22.86	.699	.364	.153
25.4	.777	.46	.153
27.94	.854	.563	.133
30.48	.932	.63	.085
33.02	1.01	.632	.045
		.597	.026
		.548	.02
		.509	.015

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

STATION NO <u>W24</u> x = <u>90.2</u> cm z = <u>15.24</u> cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.004	-.196*	.082*
.203	.007	-.204*	.081*
.305	.010	-.206*	.08 *
.404	.014	-.208*	.08 *
.508	.017	-.207*	.074*
.635	.021	-.208*	.075*
.762	.026	-.202*	.073*
1.02	.034	-.198*	.073*
1.27	.043	-.193*	.072*
1.52	.051	-.189*	.07 *
2.03	.068	-.181*	.069*
2.54	.085	-.178*	.07 *
3.05	.103	-.173*	.07 *
3.56	.120	-.17 *	.07 *
4.06	.137	-.168*	.071*
4.57	.154	-.165*	.072*
5.08	.171	-.162*	.073*
		-.161	.072
6.35	.214	-.159*	.074*
		-.159	.077
7.62	.256	-.16 *	.08 *
		-.166	.083
8.89	.299	-.172*	.088*
		-.181	.091
10.16	.342	-.192*	.094*
		-.21	.1
12.7	.427	-.202	.111
15.24	.513	.401	.109
17.78	.598	.521	.094
20.32	.684	.612	.07
22.86	.769	.665	.039
25.4	.855	.664	.024
27.94	.940	.632	.022
30.48	1.03	.592	.018
33.02	1.11	.549	.017

STATION NO <u>W28</u> x = <u>105.4</u> cm z = <u>15.24</u> cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.004	.128	.059
.203	.010	.135	.042
.305	.015	.143	.044
.404	.020	.15	.045
.508	.025	.155	.047
.635	.032	.161	.07
.762	.038	.169	.072
1.02	.051	.178	.077
1.27	.064	.191	.081
1.52	.074	.203	.087
2.03	.102	.225	.097
2.54	.127	.243	.104
3.05	.153	.259	.111
3.56	.178	.278	.117
4.06	.204	.3	.122
4.57	.229	.318	.128
5.08	.254	.341	.131
6.35	.318	.385	.132
7.62	.382	.45	.127
8.89	.445	.515	.117
10.16	.509	.583	.103
12.7	.636	.694	.065
15.24	.763	.75	.03
17.78	.890	.741	.022
20.32	1.02	.758	.019
22.86	1.14	.751	.017

STATION NO <u>W31</u> x = <u>119.4</u> cm z = <u>15.24</u> cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.018	.444	.095
.203	.017	.462	.095
.305	.025	.472	.094
.404	.033	.483	.091
.508	.042	.487	.089
.635	.052	.494	.09
.762	.063	.502	.09
1.02	.084	.51	.09
1.27	.105	.514	.092
1.52	.125	.527	.094
2.03	.167	.54	.099
2.54	.209	.559	.102
3.05	.251	.575	.106
3.56	.293	.589	.107
4.06	.334	.611	.107
4.57	.374	.635	.107
5.08	.418	.64	.103
6.35	.523	.707	.093
7.62	.627	.775	.071
8.89	.732	.825	.048
10.16	.836	.845	.032
12.7	1.05	.945	.024
14.22	1.17	1.004	.023

STATION NO <u>W34</u> x = <u>140.3</u> cm z = <u>15.24</u> cm			
y, cm	y/δ	U _{eff} /U _{ref}	u _{eff} /U _{ref}
.127	.010	.614	.099
.203	.017	.641	.1
.305	.025	.673	.099
.404	.034	.69	.097
.508	.042	.697	.094
.635	.052	.704	.092
.762	.063	.707	.091
1.02	.084	.712	.088
1.27	.105	.718	.088
1.52	.126	.719	.089
2.03	.168	.725	.091
2.54	.209	.731	.094
3.05	.251	.736	.096
3.56	.293	.745	.099
4.06	.335	.754	.101
4.57	.377	.764	.1
5.08	.419	.774	.099
6.35	.524	.798	.092
7.62	.628	.824	.078
8.89	.733	.847	.061
10.16	.838	.859	.045
12.7	1.05	.869	.024
13.97	1.15	.87	.023

*DATA OBTAINED FROM HOT-FILM PROBE ROTATED 180 DEGREES

TABLE V HOT-FILM TRAVERSE DATA (Cont'd)

TABLE VI
STREAMLINE COORDINATES DETERMINED FROM LASER VELOCIMETER MEAN
VELOCITY DATA

STREAMLINE NO.	X LOCATION																Y-COORDINATE (cm)
	26.7	31.8	40.6	48.3	52.1	55.9	59.7	67.3	74.9	82.6	90.2	97.8	105.4	113.0	119.4	140.3	
	10.5	12.5	16.0	19.0	20.5	22.0	23.5	26.5	29.5	32.5	35.5	38.5	41.5	44.5	47.0	55.25	
1	0.00	0.00	0.00	3.10	4.62	6.99	8.94	14.35	16.99	15.95	11.76	4.37	0.00	0.00	0.00	0.00	
2	1.27	1.55	2.77	5.56	7.14	9.37	11.20	16.54	19.08	18.16	14.45	8.66	3.84	1.85	1.32	1.07	
3	2.54	2.95	4.45	7.49	9.19	11.43	13.54	18.82	21.26	20.45	16.89	11.51	6.65	3.86	2.90	2.26	
4	3.81	4.32	6.05	9.25	11.05	13.46	15.77	21.03	23.39	22.61	19.08	14.07	9.17	5.89	4.55	3.61	
5	5.08	5.69	7.65	10.97	12.95	15.44	17.93	23.19	25.53	24.77	21.18	16.48	11.51	7.92	6.22	5.13	
6	6.35	7.06	9.17	12.70	14.73	17.35	19.96	25.30	27.64	26.92	23.24	18.75	13.72	9.83	7.87	6.68	
7	7.62	8.41	10.67	14.35	16.48	19.23	22.02	27.46	29.82	29.08	25.32	20.90	15.80	11.58	9.37	8.23	
8	8.89	9.73	12.14	15.98	18.21	21.13	24.16	29.72	32.11	31.32	27.53	23.04	17.83	13.31	10.80	9.73	
9	10.16	11.02	13.59	17.60	19.94			32.16			29.87	25.20	19.84	14.99	12.17	11.18	

TABLE VII
BACKFLOW BOUNDARY LAYER PARAMETERS

STATION NO.	x, cm	N, cm	U_N/U_{ref}	NU_T/ν	C_f'	Re_θ	$C_f Re_\theta$	H
25	94.0	0.097	0.156	—	0.0221	38	0.84	1.98
24	90.2	0.15	0.191	—	0.0163	57	0.93	1.90
23	86.4	0.25	0.210	—	0.0149	62	0.92	1.87
22	82.6	0.50	0.202	—	0.0090	125	1.13	1.70
21	78.7	0.63	0.194	60	0.0124	111	1.38	1.59
20	74.9	0.50	0.192	125	0.0105	124	1.30	1.61
19	71.1	0.51	0.178	110	0.0081	184	1.49	1.60
18	67.3	0.76	0.154	155	0.0076	174	1.32	1.54
17	63.5	0.76	0.139	147	0.0074	158	1.17	1.55
16	59.7	0.76	0.126	132	0.0059	174	1.03	1.48

PARAMETERS FOR TURBULENT BOUNDARY LAYER UNDER CONSTANT PRESSURE COLES (REF. 30)	240	0.00590	425	2.51	1.535
	500	0.00426	1150	4.88	1.445
	1000	0.00340	2650	8.94	1.390
	2000	0.00290	5650	16.36	1.350

APPENDIX A

LASER VELOCIMETRY SYSTEM

A.1 System Description

The LV system (fig. 3-8) consisted of a 2W argon-ion laser, a backscatter optical system employing a Bragg cell and a 3.75X beam expander, a TSI 1990B counter type signal processor, a PDP 11/10 computer for on-line data reduction, and a 7.8 MB hard disk with integral 8 in floppy disk backup for data storage (and subsequent off-line data reduction). Traversing capability was achieved by mounting the laser and optical system on a lathe bed. All system components are commercially available.

The LV was operated in a dual beam or "fringe" mode in which light from the intersection of two incident beams is heterodyned to detect the Doppler shift from an injected seed particle moving, at the local, instantaneous fluid velocity. In this mode, the LV measures the velocity component in the plane of the incident beams that is perpendicular to the bisector of the beams. The effective shape of the resultant measurement volume is an ellipsoid with major axis in the direction of the bisector of the beams. Sketch A (p. 21) shows these features and the theoretical measurement volume dimensions assuming that the ellipsoidal surface is defined by the locus of points where Doppler signal amplitude is $1/e^2$ of its centerline value. No direct measurement of the effective measurement volume size was made; it can be effected by signal amplitude and the signal processor threshold level setting. To obtain maximum resolution, the major axis was aligned in the spanwise direction. Resolution of the LV system was quite high when compared to the relevant dimensions of the experiment. The minor axis of the measuring ellipsoid, d_m , was $1/850$ of the inlet boundary layer thickness and the major axis was $1/560$ of the test section width.

A.2 Optical System

The optical system, used a 3.75X beam expander, a relatively wide angle lens ($\kappa = 4.9$ deg), and 152 mm dia optics to produce a sufficiently high signal/noise ratio (SNR) to permit measurements to be made in the backscatter mode. The SNR was enhanced by a factor of 45 compared to an equivalent optical package using standard 50 mm dia optics without a beam expander. Focal length (762 mm) of the transmitting and collecting lens was set by the transverse dimensions of the test section. A 10 MHz Bragg shift was used to eliminate directional ambiguity and to provide 360 deg acceptance angle for all particle velocities. The 10 MHz Bragg shift was accomplished by upshifting the frequency of one incident beam by 40 MHz and downshifting the collected Doppler signal by 30 MHz.

A.3 Signal Processor

The TS1 1990B counter-type signal processor featured user selectable measurement modes, fringe count ($N_f = 2^N$, $N = 1$ to 7), validation accuracy (1% to 20% in 9 increments), input gain, and large amplitude signal rejection level (i.e. large particle discriminator). Four measurement modes were available: (1) continuous mode (CONT) in which a measurement is made each time the minimum number of cycles is satisfied; (2) single measurement per burst mode (SM/B); (3) total burst count mode (TBC) in which the number of cycles in the burst are the Doppler frequency of the first N_f cycles are measured; (4) total burst mode (TBM) in which the duration of the burst and number of cycles in the burst are measured. The CONT mode was used for all measurements reported herein and the SM/B mode was used at selected points for redundancy. The CONT mode was chosen to minimize individual realization bias errors (see discussion below). Note also the CONT mode data is a superset of SM/B data because CONT data can be processed using the measured time between data points as a discriminator to eliminate multiply counted samples per burst to yield SM/B data.

A.4 Data Processing and Storage

The time period and the time between samples for each CONT sample obtained in this test program has been stored and retained on floppy disks to permit future additional processing.

After trial-and-error testing the 32 fringe count setting was found to yield an optimal combination of high data rate and "clean" histograms having minimal spurious data points in the tails. In this setting data validation is performed by making a 5/8 comparison between the time period for 20 cycles and the time period for 32 cycles. Validation accuracy was chosen to be 2% which permitted signals from seed particles following turbulence fluctuations up to approximately 25 kHz to be accepted. The signal gain and large amplitude signal rejection level were adjusted to reject 10 to 25% of the Doppler bursts to eliminate particle by biasing.

Based upon the uncertainty analysis in Appendix C and the large turbulence levels generated by the separation bubble, 2000 samples were acquired per data point to generate velocity histograms for mean velocity and turbulence intensity measurements. For Reynolds stress measurements the previously measured local turbulence intensity was used to determine whether 2000, 4000, or 8000 samples per data point were required to obtain the desired accuracy. Additional details concerning LV data processing are given in Appendix C.

A.5 Seeding System

Titanium dioxide powder having a nominal particle size of $1.0\text{ }\mu\text{m}$ was dispersed into the tunnel airstream to provide highly reflective light scattering centers for LV measurements using a fluidized bed seeding system driven by a low pressure dry air supply. A mixture of titanium dioxide powder and Cab-o-Sil, a silicon deagglomerating agent, were fluidized in the seeder to produce a densely seeded airstream which was directed to the tunnel. The seed was injected into the tunnel just downstream of the aftermost turbulence suppression screen using a cylindrical seeder probe, shown in figure A-1, which was designed to minimize the disturbance to the tunnel airstream. A similarly configured probe, designated the "zero-wake seeder" has been developed independently by Simpson (ref. 55). In principle, the flowrate through the seeder is adjusted until the momentum of the seeded air injected into the base region of the cylinder equals the cylinder drag and eliminates the wake deficit. Optimal seeder probe operation was achieved using a dry air supply pressure of 7 psi. Residual turbulence in the seeder wake was reduced by the 4 to 1 tunnel contraction. Total pressure probing revealed no discernible wake deficit at the test section inlet during seeder operation. Similarly, hot-wire measurement showed no difference in freestream turbulence level at the test section inlet during seeder operation compared to the clean tunnel operation with the seeder probe out of the tunnel. As expected, the turbulence level was increased when the probe was in the flow but not operating.

The seeder probe produced a seed cloud having an approximately circular cross-section with a 12.7 cm dia at the test section inlet. During LV traversing upstream of separation the seeder probe was frequently repositioned to center the measuring volume within the seed cloud. Traverses downstream of separation required infrequent probe repositioning because of the rapid diffusion of the seed cloud within the separated flow. For off-centerline traverses the seeder probe was moved to an off-centerline location.

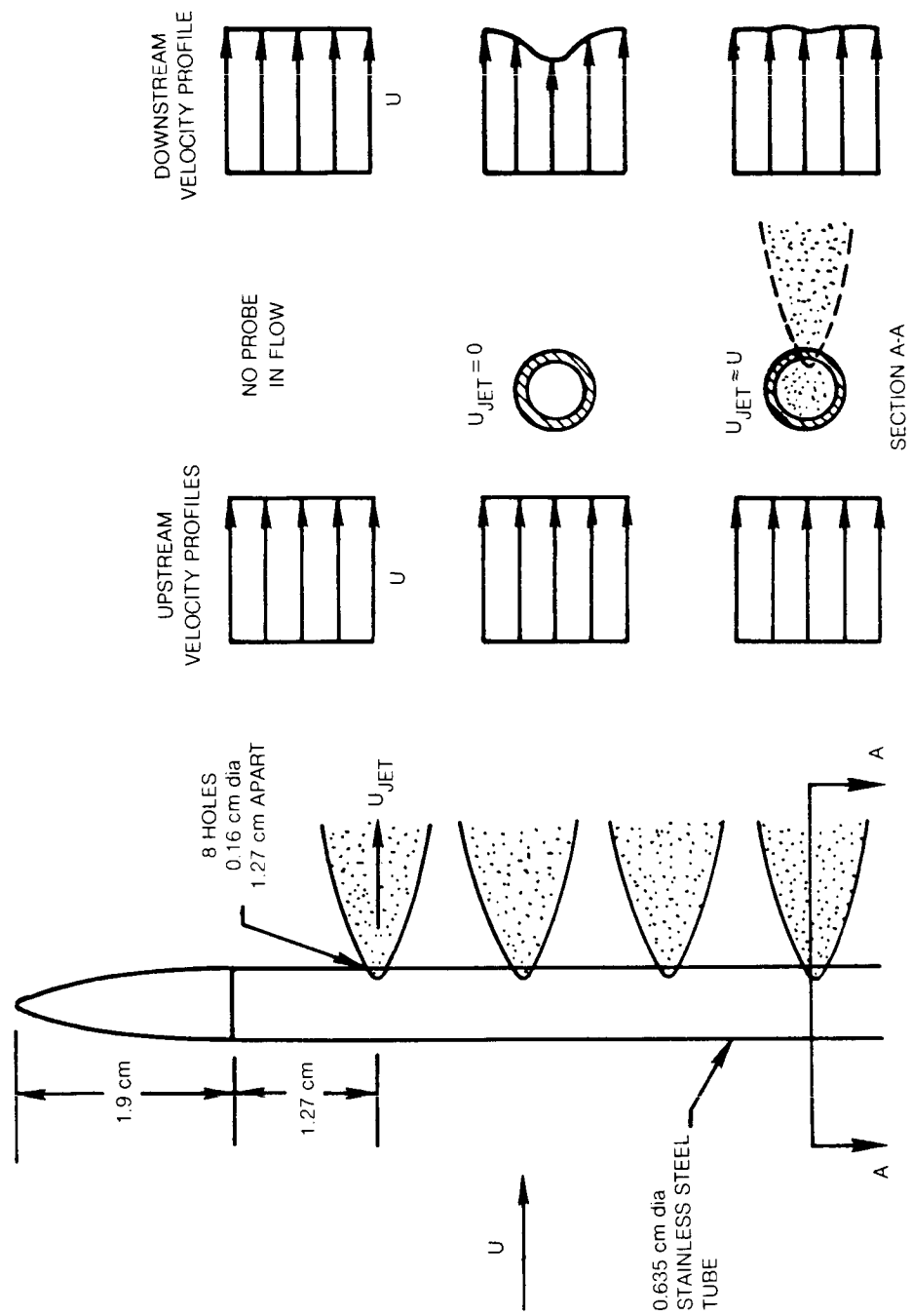


Figure A-1 Zero-Wake Seeding Probe

APPENDIX B

LASER VELOCIMETER DATA REDUCTION EQUATIONS

Figure B-1 below shows the four laser beam orientations used to extract axial and transverse velocity data with a vertical traverse of the LV measurement volume. \tilde{U}_1 , \tilde{U}_2 , \tilde{U}_3 , and \tilde{U}_4 represent the magnitudes of the instantaneous velocity in the directions indicated by the sketch during a validated particle count. Velocities \tilde{U}_1 and \tilde{U}_2 were used to measure the axial and transverse velocity fields respectively. Velocities \tilde{U}_3 and \tilde{U}_4 were used primarily to determine the Reynolds stress (\overline{uv}) and secondarily to provide redundant axial and transverse mean velocity measurements. The angle ξ was a small 5 deg laser beam inclination angle required to obtain transverse velocity and Reynolds stress measurements near the test surface. The angles α_3 and α_4 were set at 45 deg for Reynolds stress measurements.

The desired axial and transverse velocities are related to the measured velocities by the following equations:

$$\tilde{U}_1 = \tilde{U} \quad (B1)$$

$$\tilde{U}_2 = \tilde{V} \cos \xi + \tilde{W} \sin \xi \quad (B2)$$

$$\tilde{U}_3 = \tilde{U} \cos \alpha_3 - \tilde{V} \sin \alpha_3 \cos \xi - \tilde{W} \sin \xi \quad (B3)$$

$$\tilde{U}_4 = \tilde{U} \cos \alpha_4 - \tilde{V} \sin \alpha_4 \cos \xi + \tilde{W} \sin \xi \quad (B4)$$

Taking each velocity, \tilde{U} , as the sum of a mean, U , and a fluctuating part, $u(t)$, yields the mean velocity eqs. (B5) through (B8)

$$U = U_1 \quad (B5)$$

$$V = \frac{U_2}{\cos \xi} - W \tan \xi \quad (B6)$$

$$U = \frac{U_3 \sin \alpha_4 - U_4 \sin \alpha_3}{\cos \alpha_3 \sin \alpha_4 - \sin \alpha_3 \cos \alpha_4} + W \frac{\sin \xi (\sin \alpha_3 + \sin \alpha_4)}{\cos \alpha_3 \sin \alpha_4 - \sin \alpha_3 \cos \alpha_4} \quad (B7)$$

$$V = \frac{U_4 \cos \alpha_3 - U_3 \cos \alpha_4}{\cos \xi (\cos \alpha_3 \sin \alpha_4 - \sin \alpha_3 \cos \alpha_4)} - W \frac{\tan \xi (\cos \alpha_3 + \cos \alpha_4)}{\cos \alpha_3 \sin \alpha_4 - \sin \alpha_3 \cos \alpha_4} \quad (B8)$$

The measurement of U and V are redundant because eqs. (B5) and (B6) are independent from eqs. (B7) and (B8).

Evaluating eqs. (B7) and (B8) for $\alpha_3 = +45$ deg and $\alpha_4 = -45$ deg yields considerably simplified eqs. (B9) and (B10).

$$U = \frac{\sqrt{2}}{2} (U_3 + U_4) \quad (B9)$$

$$V = \frac{\sqrt{2}}{2 \cos \xi} (U_3 - U_4) - \sqrt{2} W \tan \xi \quad (B10)$$

Squaring, time averaging, and subtracting the mean flow equations yields equations for the axial and transverse turbulence intensities.

$$\overline{u^2} = \overline{u_1^2} \quad (B11)$$

$$\overline{v^2} = \frac{\overline{u_2^2}}{\cos^2 \xi} - 2 \overline{vw} \tan \xi - \overline{w^2} \tan^2 \xi \quad (B12)$$

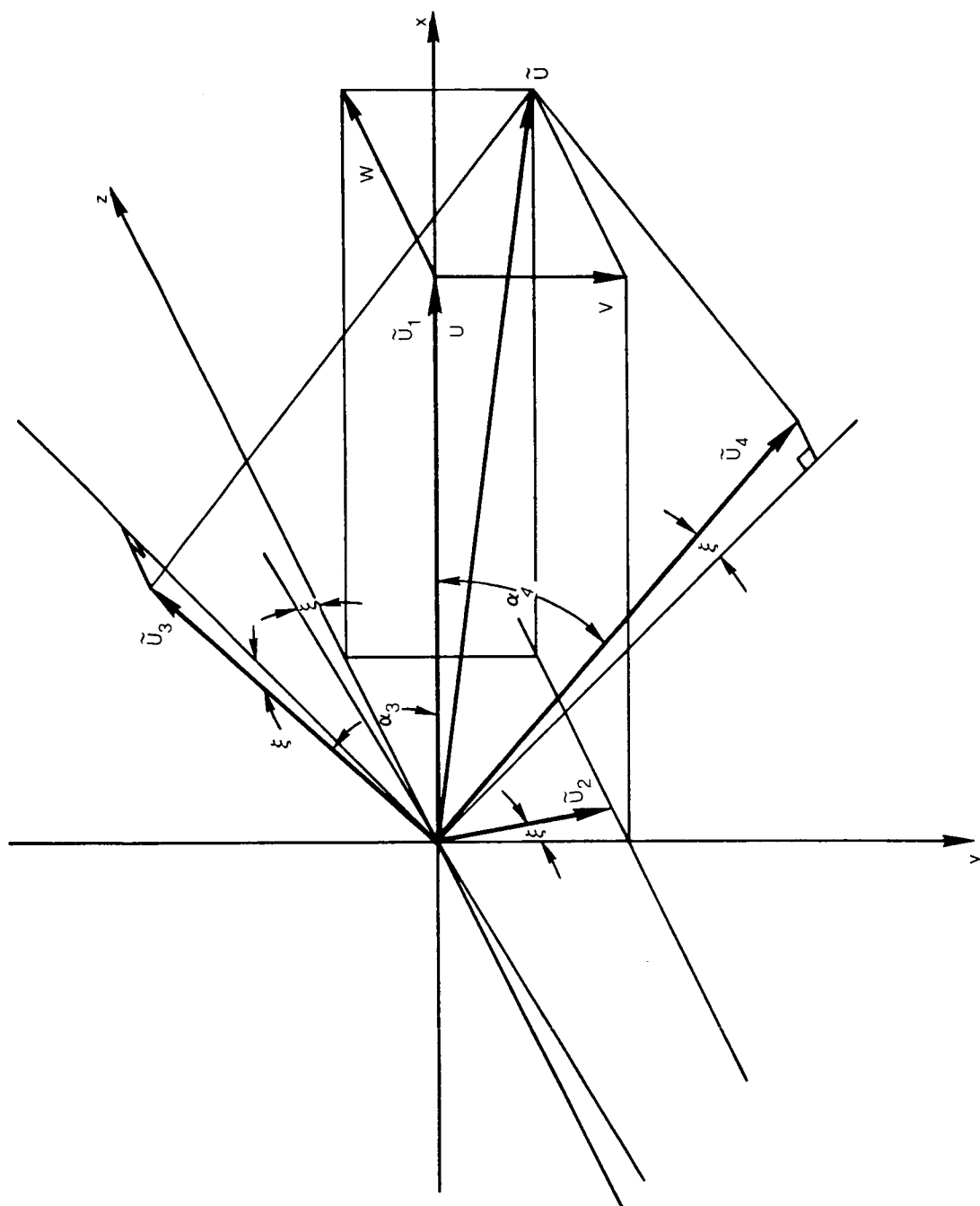
and the Reynolds stress

$$\overline{uv} = \frac{1}{2 \cos \xi} (\overline{u_4^2} - \overline{u_3^2}) - \sqrt{2} \overline{uw} \tan \xi \quad (B13)$$

after setting $\alpha_3 = +45$ deg and $\alpha_4 = -45$ deg.

In evaluating equations (B6) and (B10-13) only the first terms on the right hand side were used. The additional correction terms, which contained

unmeasured spanwise velocity components, were very small because of the two-dimensionality of the flow ($W \approx 0$) and the small inclination angle ($\xi = 5$ deg). Away from the immediate vicinity of the wall ($\xi = 0$) the correction terms disappeared.



APPENDIX C

LV ERROR ANALYSIS

A procedure for quantifying LV measurement errors has been developed (ref. 37) in conjunction with the present study as part of UTRC's independent research activities in gas dynamics. This uncertainty analysis includes the consideration of fixed (bias) and precision (random) errors and the methods for calculating the propagation of measurement errors through the system. Errors in the LV measurement system have been categorized as: (1) data processing errors, (2) laser beam geometrical errors, (3) processor errors, and (4) errors associated with seeding. Data processing errors arise from averaging a finite number of data samples per data point. Processor errors are the clock synchronization error, the quantizing error, the threshold limit error, the pedestal removal filter error, and the electronic noise induced errors. Laser beam geometrical errors include positioning uncertainty of the probe volume, angular sensitivity of the probe volume, fringe spacing uncertainty, and beam orientation errors, as well as, limitations imposed by a finite-sized probe volume. Seeding errors include flow distortion caused by seed injection, errors associated with the arrival rate of seed passing through the probe volume (individual realization bias), and particle lag errors in accelerating (or decelerating) flowfields.

In this Appendix the error analysis presented in reference 37 will be summarized briefly. The error analysis methodology including the definition of terms, the determination of measurement uncertainty, and the propagation of measurement errors will be explained. Then, each error source will be described briefly. Finally, values of the precision and bias errors for the current experiment will be calculated and combined to determine estimates of the total uncertainty of LV measurements throughout the flowfield.

C.1 Error Analysis Methodology

C.1.1 Definition of Terms

An error is the difference between the measurement and the true value of the parameter being measured. Uncertainty is the maximum error which reasonably might be expected in a parameter which is measured or which is computed from measured data. Measurement errors are of two types, random (or precision) errors and fixed (or bias) errors.

Random errors occur because of variations in repeated measurements of the same parameter. The precision index, S , is an estimate of the random (or precision) error. For N measurements ($X_1, X_2, \dots, X_i, \dots, X_N$) of the parameter X the precision index is defined as

$$S = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N - 1}} \quad (C-1)$$

where \bar{X} , the mean of the measured values, is defined as

$$\bar{X} = \frac{1}{N} \sum_{i=1}^N X_i \quad (C-2)$$

Bias is the fixed or systematic error. In repeated measurements, each measurement has the same bias, as illustrated in figure C-1. Examples of bias errors encountered in LV measurements are laser beam geometrical errors, process errors, and errors associated with seeding.

C.1.2 Determination of Measurement Uncertainty

The uncertainty is determined by combining the precision and bias errors in the following manner:

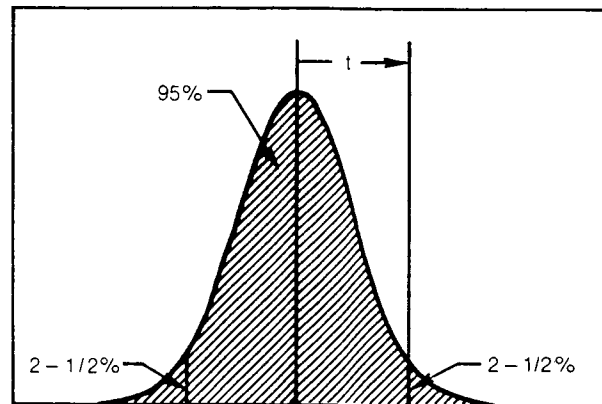
$$U = \pm (B + t_{95} S) \quad (C-3)$$

where B is the bias limit and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (ref. 56). When the bias limit is non-symmetric, upper ($U^+ = B^+ + t_{95} S$) and lower ($U^- = B^- - t_{95} S$) uncertainty limits are calculated. The t_{95} value is a function of the number of degrees of freedom used in calculating S as shown in Table C-1. In a sample, the number of degrees of freedom is the size of the sample. For a statistic calculated from the sample the number of degrees of freedom is reduced by one for every estimated parameter used in calculating the statistic. For example, the mean, \bar{X} , calculated from the sample (eq. (C-2)) has N degrees of freedom and the precision index, S, calculated from the mean (eq. (C-1)) has N-1 degrees of freedom.

C.1.3 Propagation of Measurement Error

Although only the uncertainty parameters, U, need be presented with the data, the bias and precision values are required to determine the propagation of the measurement error. The proper method for combining elemental measurement uncertainty values is to determine the root-sum-square values of the elemental bias limits and the elemental precision indices separately using a

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DEGREES OF FREEDOM	"t"	DEGREES OF FREEDOM	"t"
1	12.706	17	2.110
2	4.303	18	2.101
3	3.182	19	2.093
4	2.776	20	2.086
5	2.572	21	2.080
6	2.447	22	2.074
7	2.365	23	2.069
8	2.306	24	2.064
9	2.262	25	2.060
10	2.228	26	2.056
11	2.201	27	2.052
12	2.179	28	2.048
13	2.160	29	2.045
14	2.145	30	2.042
15	2.131	31 OR MORE USE 2.0	
16	2.120		

Table C-1 Two-Tailed Student's "t" Table

Taylor series expansion of the function being calculated from the elemental measurements. For example, the streamwise Reynolds stress, $\overline{\alpha\beta}$, is determined from measured values of the Reynolds stress, axial and transverse turbulence components, and the flow angle

$$\overline{\alpha\beta} = \overline{uv} (\cos^2\phi - \sin^2\phi) + (\overline{v^2} - \overline{u^2}) \sin\phi \cos\phi \quad (C-4)$$

The precision index for the streamwise Reynolds stress, $s^{\overline{\alpha\beta}}$, can be determined as

$$s^{\overline{\alpha\beta}} = \left\{ \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{uv})} s^{\overline{uv}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{v^2})} s^{\overline{v^2}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{u^2})} s^{\overline{u^2}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial\phi} s^\phi \right]^2 \right\}^{1/2} \quad (C-5)$$

Performing the indicated differentiation yields

$$s^{\overline{\alpha\beta}} = \left\{ \left[(\cos^2\phi - \sin^2\phi) s^{\overline{uv}} \right]^2 + \sin^2\phi \cos^2\phi \left[\left(s^{\overline{u^2}} \right)^2 + \left(s^{\overline{v^2}} \right)^2 \right] + \left[(\overline{v^2} - \overline{u^2}) (\cos^2\phi - \sin^2\phi) - 4\overline{uv} \sin\phi \cos\phi \right]^2 (s^\phi)^2 \right\}^{1/2} \quad (C-6)$$

Similarly, the bias limit of the calculated streamwise Reynolds stress, $B^{\overline{\alpha\beta}}$, is propagated from the bias limits of the measured variables.

$$B^{\overline{\alpha\beta}} = \left\{ \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{uv})} B^{\overline{uv}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{v^2})} B^{\overline{v^2}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial(\overline{u^2})} B^{\overline{u^2}} \right]^2 + \left[\frac{\partial(\overline{\alpha\beta})}{\partial\phi} B^\phi \right]^2 \right\}^{1/2} \quad (C-7)$$

To propagate nonsymmetrical bias limits, the bias limit portion of the analysis must be completed for both the upper and the lower limits. The uncertainty in the calculated value of U is then determined by combining the bias and precision indices as shown in eq. (C-3).

C.2 Data Processing (Precision) Errors

Data processing errors are precision errors which arise from averaging a finite number of data samples per data point. In general, the precision error for any finite number of measurements of a fixed quantity can be calculated using eqs. (C-1) and (C-2). However, in LV velocity measurements, the velocity being measured does not remain constant during the sampling period but fluctuates due to turbulence. Thus, for LV measurements, equations (C-1) and (C-2) can be written in the form

$$S = \sqrt{\frac{\sum_{i=1}^N (U_i - U)^2}{N-1}} \quad (C-8)$$

$$U = \frac{1}{N} \sum_{i=1}^N U_i \quad (C-9)$$

where U_i is the velocity of the i th sample and U is the sample mean velocity which is an unbiased estimate of U_p , the population mean velocity. The precision (or random) error calculated by eq. (C-8) is an estimate of the rms turbulence level of the flow being sampled. In the limit of an infinite number of samples, S becomes an exact measurement of the turbulence level. For a finite number of samples both the indicated rms turbulence level calculated in eq. (C-8) and the mean sample velocity calculated in eq. (C-9) will deviate from the true turbulence level and mean velocity of the flowfield by precision errors S^{ζ} and S^U respectively.

C.2.1 Precision Errors in Turbulence Measurements

Since the mean square turbulence velocity has a Chi-squared distribution (ref. 57) S^{ζ} can be obtained from tables by entering the number of degrees of freedom, $N-1$. For a large sample size, however, the inconvenient tables are unnecessary since

$$\frac{S^{\zeta}}{\zeta} = \frac{1}{\sqrt{2N}} \quad N > 50 \quad (C-10)$$

Values of the precision error in turbulence measurement are calculated for various sample sizes typical of LV measurements in Table C-2. In the present study 2000 samples were taken to acquire each turbulence measurement. Thus, the precision error in the measurement of the turbulence component is ± 1.58 percent of the turbulence magnitude.

TABLE C-2. PRECISION ERROR IN TURBULENCE MEASUREMENT, s^2/ζ

N	s^2/ζ
500	.0316
1000	.0224
2000	.0158
4000	.0112
8000	.0079

C.2.2 Precision Errors in Mean Velocity Measurements

Relative to mean velocity measurements, the sampling distribution of U is normal about U_p as a mean with a standard deviation u_p/\sqrt{N} . Thus, the precision error in the mean velocity measurement can be estimated as

$$\frac{s^U}{U_p} = \frac{\zeta}{\sqrt{N}} \quad (C-11)$$

which is a function of the turbulence level. U_p and ζ are unknown but can be approximated by the measured quantities U and $\sqrt{u^2}/U$. Values of the precision error in mean velocity measurement for turbulence levels and sampling sizes typical of LV measurements are given in Table C-3. Note that both the

TABLE C-3. PRECISION ERRORS IN MEAN VELOCITY MEASUREMENT, $\frac{s^U}{U_{ref}} \times 10^2$

N	$\frac{\sqrt{u^2}}{U_{ref}} \times 100$			
	1%	5%	15%	25%
500	.045	.224	.671	1.118
1000	.032	.158	.474	.791
2000	.022	.112	.335	.559
4000	.016	.079	.237	.395
8000	.011	.056	.168	.280

precision error and the turbulence level have been normalized by U_{ref} to avoid extreme local turbulence levels which occur in regions of the flow where $U \approx 0$. Since 2000 samples were acquired to obtain each mean velocity measurement, the precision error in mean velocity varies from $\pm 0.02\%$ in regions of low turbulence intensity ($\sqrt{u^2}/U_{ref} = 0.01$) to $\pm 0.56\%$ in regions of high turbulence ($\sqrt{u^2}/U_{ref} = 0.25$).

The precision error in Reynolds stress measurements obtained with a one-component LV system can be shown to be (ref. 37)

$$S_1^{\overline{uv}} = \sqrt{2} \zeta S^{\zeta} \quad (C-12)$$

The precision error in the streamwise shear stress component, $\overline{\alpha\beta}$, can then be calculated using eq. (C-6). Calculated values of the precision error in the Reynolds stress and the streamwise shear stress measurements for each data point are presented in Table III.

C.3 Bias Errors

C.3.1 Laser Beam Geometrical Errors

C.3.1.1 Finite Probe Volume Bias (PVB)

Finite probe volume bias occurs because LV measurements represent a spatial average of the velocity throughout the probe volume rather than at a point in space. This bias error tends to increase the turbulence measurement and may increase or decrease the mean velocity measurement depending on the velocity gradients within the probe volume.

C.3.1.2 Beam Location Bias (BLB)

Beam location bias is caused by the uncertainty in positioning the probe volume within the test section. It can be calculated as the product of the estimated velocity or turbulence gradients and the positional uncertainty in the direction of the gradient.

C.3.1.3 Beam Orientation Bias (BOB)

Two types of bias errors arise from beam orientation errors. The first type, B_e , which effects all measurements, is caused by misalignment of the laser beams relative to the rig axis. The second type, B_{45} , is caused by the uncertainty in setting ± 45 degree beam orientation during shear stress measurements.

C.3.1.4 Fringe Spacing Uncertainty (FSB)

This bias is due to the uncertainty in the fringe spacing caused by the error, $\Delta\kappa$, in setting the angle, κ , between the intersecting laser beams.

C.3.1.5 Negative Velocity Beam (NVB)

The laser velocimeter measures the relative speed between the seed particles in the flow and the fringes in the measurement volume. If the fringe pattern is stationary the LV system cannot discriminate between seed particles traveling in the positive or negative directions. The LV processor thus rectifies the velocity signal in the same manner as a hot-wire. Consequently, in flow fields containing regions or periods of flow reversal the ensemble-averaged velocity will be biased high and the turbulence level will be biased low. When a Bragg shift is used to move the fringes in the negative direction at a velocity greater than the maximum negative velocity, NVB is eliminated.

C.3.1.6 Incomplete Signal Bias (ISB)

Incomplete signal bias is caused by the angular sensitivity of the measurement volume. The probability that a seed particle passing through the measurement volume will cross the minimum number of fringes required to register a valid velocity sample decreases as the angle between the seed particle velocity vector and the normal to the fringe plane increases. Bragg shifting can be used, however, to achieve near isotropic response to eliminate ISB.

C.3.1.7 Frequency Broadening Bias (FBB)

Frequency broadening bias occurs when the laser beams do not intersect at the beam waists, where the wavefronts are plane, but elsewhere where the wavefronts have a finite radius of curvature. The resulting measurement volume has spatial variations in the fringe spacing. In a properly designed and aligned LV system the beams will intersect at the beam waists and frequency broadening will be eliminated.

C.3.2 Processor Bias Errors

C.3.2.1 Comparison Accuracy Biases (CAB)

Comparison accuracy biases occur in flows in which individual particle velocity changes within the probe volume normal to the fringe pattern are significant. When changes in velocity occur within the probe volume, the comparator on the LV processor may reject valid signals causing a bias. Two types of comparison accuracy biases are particle acceleration bias (PAB) which

can occur in strong acceleration or deceleration fields and comparator tolerance bias (CTB) which can occur in highly turbulent flows due to changes in flow direction within the probe volume and/or particle velocity changes induced by swirling turbulent eddies.

C.3.2.2 Clock Synchronization Error (CSB)

The clock synchronization error is the bias caused by the mismatch between the randomly occurring Doppler burst and the start of the clock cycle in the processor. The uncertainty ranges from 0 to -1 clock pulse with all values in between being equally probable.

C.3.2.3 Quantizing Error (QB)

The quantizing error is the bias arising from the determination of the frequency of the analog Doppler signal using the digital reference clock in the processor. The quantized time interval determined by the clock is accurate to within ± 1 clock pulse with all values in between being equally probable.

C.3.2.4 Threshold Limit Error (TLB)

The threshold limit error is the bias caused by the use of a non-zero volt Schmitt trigger in the processor to digitize the Doppler burst. The processor used in the current study used a true-zero-crossing detector which eliminated this bias.

C.3.2.5 Electronic Noise Induced Error (ENB)

The electronic noise induced error is the bias which occurs at low signal-to-noise ratios (SNR) when electronic noise mixed with the Doppler signal causes incorrect LV measurements. This bias can be significantly reduced by data validation circuitry within the processor and by operating at $\text{SNR} > 5$.

C.3.2.6 Pedestal Filter Removal Error (PFB)

This error is caused by the improper setting of the cutoff frequency of the high-pass pedestal removal filter. If the cutoff frequency is set too high, the Doppler burst caused by a low velocity particle will be distorted by the filter or even dropped out causing the velocity estimate from the LV processor to become biased high. If the cutoff frequency is at too low, some high velocity bursts will pass through the filter with residual pedestals causing a biased velocity estimate of the distorted frequency packet.

C.3.3 Seeding Bias Errors

C.3.3.1 Flow Distortion Bias (FDB)

Flow distortion bias occurs when the mean flowfield is distorted by the seed injection process. Small seed particles, which have been sized to follow the flow, cannot be dispersed across the tunnel cross section except by natural diffusion. They cannot be projected across flow streamlines but instead must be convected with the seed injection jet.

C.3.3.2 Particle Lag Bias (PLB)

The accuracy of LV flow velocity measurements is limited by the ability of the seed particles, which reflect the laser light, to move at the same velocity as the surrounding fluid. When the seed particles are too large to accurately follow rapid oscillations in the flowfield, particle lag bias occurs.

C.3.3.3 Individual Realization Bias (IRB)

If the seed particles are distributed uniformly in space the number of particles passing through a unit volume in the flowfield varies directly with the particle velocity. High velocity regions of the flow contribute more LV samples per unit time than low velocity regions. In a shear layer or in turbulent flow the LV probe volume will span a region of the flow having both high and low flow velocities. In such cases the ensemble average velocity will be larger than the time-mean velocity of the flow because of the increased number of high velocity samples in the ensemble. A detailed discussion of this individual realization bias and correction schemes to reduce it are presented in reference 37.

C.3.3.4 Bragg Bias (BB)

When the LV processor is operated in a continuous sampling mode while a Bragg shift is used to move the fringe pattern, slower particles will be multiply sampled more often than faster particles because they spend more time in the probe volume. This effect has been termed Bragg bias and it partially offsets individual realization bias.

C.4 Determination of Total Uncertainty

Before the uncertainty of LV measurements could be evaluated using the equations and graphs given in reference 37, the parameter values listed in Table C-4 were estimated. These parameter values included probe volume dimensions, processor settings, seed particle characteristics, estimates of the

TABLE C-4
PARAMETER VALUES USED IN LV ERROR ANALYSIS

FLOW PARAMETERS:

$$U_{\max} = 27.4 \text{ m/sec}, V_{\max} = 12.2 \text{ m/sec}, w = 0, \phi = 30 \text{ deg}$$

$$\left. \frac{\Delta U}{\Delta x} \right|_{\max} = 100/\text{sec}, \left. \frac{\Delta U}{\Delta y} \right|_{\max} = 1920/\text{sec}, \frac{\Delta U}{\Delta z} = 0$$

$$\left. \frac{\Delta V}{\Delta x} \right|_{\max} = 200/\text{sec}, \left. \frac{\Delta V}{\Delta y} \right|_{\max} = 100/\text{sec}, \frac{\Delta V}{\Delta z} = 0$$

$$\frac{\Delta W}{\Delta x} = \frac{\Delta W}{\Delta y} = \frac{\Delta W}{\Delta z} = 0$$

$$\left. \frac{1}{\zeta} \frac{\partial \zeta_x}{\partial x} \right|_{\max} = 55/\text{m} \quad \left. \frac{1}{\zeta} \frac{\partial \zeta_y}{\partial x} \right|_{\max} = 25/\text{m} \quad \left. \frac{1}{\zeta} \frac{\partial \zeta_z}{\partial x} \right|_{\max} = 45/\text{m}$$

$$\left. \frac{1}{\zeta} \frac{\partial \zeta_x}{\partial y} \right|_{\max} = 160/\text{m} \quad \left. \frac{1}{\zeta} \frac{\partial \zeta_y}{\partial y} \right|_{\max} = 32/\text{m} \quad \left. \frac{1}{\zeta} \frac{\partial \zeta_z}{\partial y} \right|_{\max} = 1/\text{m}$$

$$\frac{1}{\zeta} \frac{\partial \zeta_x}{\partial z} = \frac{1}{\zeta} \frac{\partial \zeta_y}{\partial z} = \frac{1}{\zeta} \frac{\partial \zeta_z}{\partial z} = 0$$

BEAM GEOMETRY:

$$M = 32, N_f = 44, f_B = 10.16 \text{ MHz}, \text{SNR} = 40$$

$$d_m = 133 \mu\text{m}, l_m = 1.6 \text{ mm}, d_f = 3 \mu\text{m}$$

$$\Delta x = \pm 2 \text{ mm}, \Delta y = \pm .025 \text{ mm}, \Delta z = \pm 1 \text{ mm}, \Delta \phi = \pm .25 \text{ deg}$$

$$\kappa = 4.9 \text{ deg}, \Delta \kappa = \pm .01 \text{ deg}$$

PROCESSOR PARAMETERS: $f_c = 500 \text{ MHz}$, $\text{COMP} = 0.02$, $N = 2000$

SEED PARAMETERS:

$$\text{SEED MATERIAL, TiO}_2: d_p = 1 \mu\text{m}$$

maximum mean flow and turbulence gradients in each of the three coordinate directions, and uncertainties in laser beam positioning, orientation, and intersection angle. Each of the precision and bias errors discussed in the previous sections has been evaluated to determine estimates for the total uncertainty of LV measurements of U , V , $\sqrt{u^2}$, and $\sqrt{v^2}$. The uncertainties for U and $\sqrt{u^2}$ measurements have been estimated for regions of the flowfield having moderate ($\sqrt{u^2}/U_{\text{ref}} = 0.05$) and high ($\sqrt{u^2}/U_{\text{ref}} = 0.20$) axial turbulence levels. The uncertainties for V and $\sqrt{v^2}$ measurements have been estimated for regions of the flowfield having an intermediate transverse turbulence level ($\sqrt{v^2}/U_{\text{ref}} = 0.10$). Values for each error source and the total uncertainties are listed in Table C-5.

When evaluating the uncertainties several biases were assumed to be negligible. They are the pedestal removal filter error (PFB), the threshold limit error (TLB), the finite probe volume bias (PVB), particle acceleration bias (PAB), negative velocity bias (NVB), frequency broadening bias (FBB), and flow distortion bias (FDB). The negligible values for these biases follow respectively from the following assumptions: the pedestal removal filter has been set correctly, the processor has a true-zero-crossing detector, the probe volume is small compared to any spatial velocity gradients in the flowfield (PVB and PAB), Bragg shifting was used in regions of reversed flow, the laser beams intersected at the beam waists, and the zero-wake seeder probe caused negligible flowfield distortion at the measurement location.

As shown in Table C-5, none of the processor bias errors exceeds $\begin{smallmatrix} +.06 \\ -.01 \end{smallmatrix}$ percent. For mean velocity measurements beam geometry biases are also very low, the highest being the $\pm 0.7\%$ bias due to uncertainty in probe volume location (BLB). The combined effect of seed bias errors on the mean velocity uncertainty is also very small. Particle lag bias, estimated from figure 8 in reference 37, is approximately 0.1 percent in both U and V components. The individual realization bias in the U component measurement would have been large ($\begin{smallmatrix} +0.040 \\ -0 \end{smallmatrix}$) in regions of high turbulence level ($\sqrt{u^2}/U_{\text{ref}} = 0.20$) but it was offset by Bragg bias because the processor was operated in the continuous sampling mode. Thus, the total bias from all sources is ± 0.0080 and $\begin{smallmatrix} +0.013 \\ -0.0087 \end{smallmatrix}$ for U and V measurements, respectively. When combined with the precision error estimated for 2000 sample measurements, the uncertainty in LV measurements of U is ± 0.010 and ± 0.017 in regions of moderate ($\sqrt{u^2}/U_{\text{ref}} = 0.05$) and high ($\sqrt{u^2}/U_{\text{ref}} = 0.20$) turbulence, respectively. The estimated uncertainty in the transverse velocity is $\begin{smallmatrix} +0.016 \\ -0.012 \end{smallmatrix}$ in regions of intermediate transverse turbulence ($\sqrt{v^2}/U_{\text{ref}} = 0.10$). This uncertainty value means that 19 out of every 20 mean velocity measurements will be within these quoted accuracies as noted above in Section C.1.2.

TABLE C-5
ESTIMATED BIAS ERRORS, PRECISION ERRORS, AND UNCERTAINTIES OF LV MEASUREMENTS

PROCESSOR BIAS ERRORS	$\sqrt{u} \left(\frac{u}{u_{ref}} = 0.20 \right)$	$\sqrt{u} \left(\frac{u}{u_{ref}} = 0.05 \right)$	$\sqrt{v} \left(\frac{v}{v_{ref}} = 0.10 \right)$	$\sqrt{u} \left(\frac{u}{u_{ref}} = 0.20 \right)$	$\sqrt{v} \left(\frac{v}{v_{ref}} = 0.05 \right)$	$\sqrt{v} \left(\frac{v}{v_{ref}} = 0.10 \right)$
1. PARTICLE ACCELERATION BIAS (PAB)	0	0	0	0	0	0
2. COMPARATOR TOLERANCE BIAS (CTB)	0	0	0	0	0	0
3. CLOCK SYNCHRONIZATION ERROR (CSB)	+0.00064 -0	<0.01% <0.01%	+0.00030 -0	+0.00058 -0	+0.00060 -0	+0.00046 -0
4. QUANTIZING ERROR (QB)	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
5. THRESHOLD LIMIT ERROR (TLB)	0	0	0	0	0	0
6. ELECTRONIC NOISE INDUCED ERROR (ENB)	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%	<0.01%
7. PEDESTAL FILTER REMOVAL ERROR (PFB)	0	0	0	0	0	0
PROCESSOR BIAS (PB)	+0.00064 -0	<0.01%	+0.0003 -0	+0.0006 -0	+0.0006 -0	+0.0005 -0
BEAM GEOMETRY BIAS ERRORS						
1. FINITE PROBE VOLUME BIAS (PVB)	0	0	0	0	0	0
2. BEAM LOCATION BIAS (BLB)	± 0.0075	± 0.0075	± 0.0073	± 0.0051	± 0.0051	± 0.0051
3. BEAM ORIENTATION BIAS (BOB)	± 0.0019	± 0.0019	± 0.0044	± 0.0035	± 0.0035	± 0.0035
4. FRINGE SPACING UNCERTAINTY (FSB)	± 0.0020	± 0.0020	± 0.00089	± 0.0020	± 0.0020	± 0.0020
5. NEGATIVE VELOCITY BIAS (NVB)	0	0	0	0	0	0
6. INCOMPLETE SIGNAL BIAS (ISB)	0	0	0	0	0	0
7. FREQUENCY BROADENING BIAS (FBB)	0	0	0	0	0	0
BEAM GEOMETRY BIAS (BGB)	± 0.0008	± 0.0008	± 0.0086	± 0.0052	± 0.0052	± 0.0056
SEEDING BIAS ERRORS						
1. FLOW DISTORTION BIAS (FDB)	0	0	0	0	0	0
2. PARTICLE LAG BIAS (PLB)	± 0.0008	± 0.0008	± 0.0013	0	0	0
3. INDIVIDUAL REALIZATION BIAS (IRB)	+0.040 -0	+0.0025 -0	+0.010 -0	+0	+0	+0
4. BRAGG BIAS (BB)	+0 -0.040	-0 -0.0025	0	0	0	0
SEEDING BIAS (SB)	± 0.0008	± 0.0008	+0.010 -0.0013	+0 -0.050	+0 -0.005	+0 -0.010
TOTAL BIAS (B)	± 0.0080	± 0.0080	+0.013 -0.0087	+0.0552 -0.0745	+0.0552 -0.0554	+0.0362 -0.0275
PRECISION ERROR	± 0.00447	± 0.00112	± 0.00158	± 0.0158	± 0.0158	± 0.0158
TOTAL UNCERTAINTY (U)	± 0.0169	± 0.0102	+0.0182 -0.0119	+0.087 -0.106	+0.087 -0.087	+0.068 -0.059

For turbulence measurements, the bias errors are expressed as a fraction of the maximum turbulence intensity ($\zeta_{\max} = 0.25 U_{\text{ref}}$). Beam geometry biases are small except for the beam location bias which is estimated to be $\pm .055$ and $\pm .025$ for measurements of axial and transverse turbulence components, respectively. This is a worst-case estimate, assuming the maximum positioning uncertainty occurs at the location of the maximum turbulence gradient. The effect of particle lag on turbulence measurements is negligible since the 1.0 μm dia. TiO_2 seed particles can track at 2500 Hz sinusoidal oscillation to an accuracy better than 1% and most of the energy in the turbulence spectrum was in the 0-100 Hz band (fig. 4-15). The individual realization bias is estimated to be as high as $\begin{smallmatrix} +0 \\ -0 \end{smallmatrix} .050$ for axial turbulence component measurements in the high turbulence ($\sqrt{u^2}/U_{\text{ref}} = 0.20$) environment but throughout most of the flowfield IRB is less than 1%. It is assumed that Bragg bias did not effect the turbulence measurements.

When combined with the precision error (± 0.0158) estimated for a 2000 sample measurement, the uncertainty in the measurement of the axial turbulence component is ± 0.087 and $\begin{smallmatrix} +0.087 \\ -0.106 \end{smallmatrix}$ in regions of moderate and high turbulence levels, respectively. The estimated uncertainty in the transverse turbulence component measurement is $\begin{smallmatrix} +0.068 \\ -0.059 \end{smallmatrix}$ in regions of intermediate transverse turbulence level. As noted above, these uncertainty estimates are expressed as fractions of the maximum turbulence intensity ($\zeta_{\max} = 0.25 U_{\text{ref}}$) and are worst-case estimates.

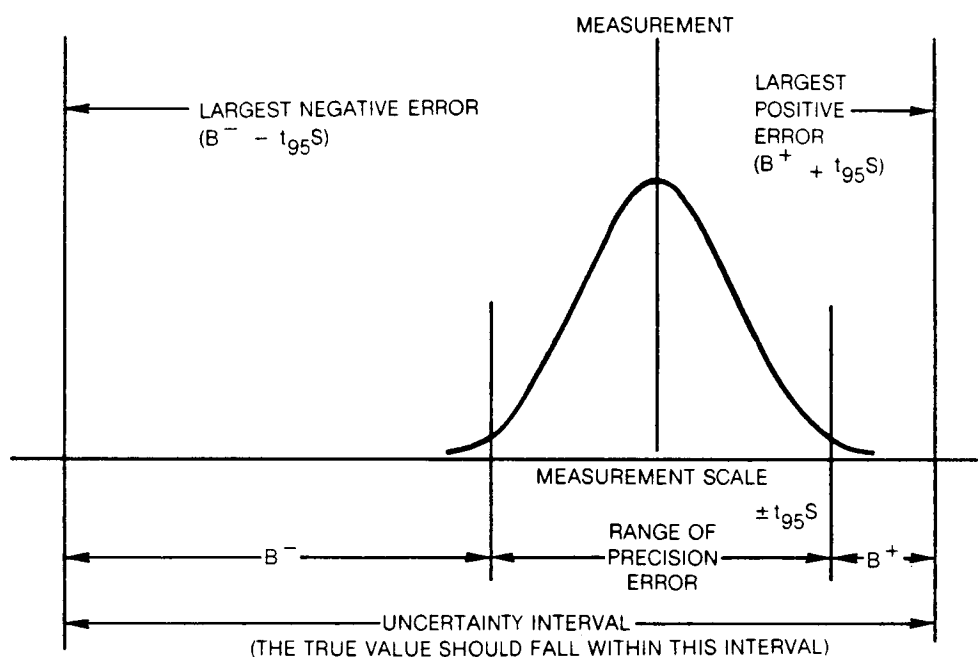


Fig. C-1 Measurement Uncertainty, Nonsymmetrical Bias

APPENDIX D

ERROR ESTIMATES FOR TOTAL PRESSURE AND HOT-FILM MEASUREMENTS

D.1 Accuracy of Total Pressure Measurements

The accuracy of the total pressure measurements is dependent on several factors including the accuracy of the pressure transducers, the angular sensitivity of the pitot probes, and the effect of turbulence on the pitot reading. Each of these factors will be discussed below.

D.1.1 Transducer Calibrations

Pressure transducers were calibrated to an accuracy of $\pm 0.0005 Q_{ref}$ with a micromanometer (fig. 3-9) at the beginning of each test day. Transducer output voltages were zeroed prior to each traverse to compensate for thermal drift. Zeroes were also checked after each traverse to ensure that drift during the traverse did not exceed $\pm 0.002 Q_{ref}$ otherwise the data was retaken.

D.1.2 Angular Sensitivity of Probes

The total pressure probes were calibrated for angular sensitivity in pitch and yaw over a ± 30 deg. range at three dynamic pressures: Q_{ref} , $0.45 Q_{ref}$, and $0.09 Q_{ref}$. The boundary layer probes were accurate to within 1% of the dynamic head pressure over ± 7 deg. relative to the normal to the probe shaft. The aspirated kielhead probes were accurate to within $0.005 Q_{ref}$ over ± 26 deg. relative to the normal to the face of the probe. The angular sensitivity of all probes used in the current study were essentially unaffected by flow speed over the range tested.

Since the boundary layer probes were only used to obtain data near the test surface ($y < 2$ cm) where the mean flow inclination angle was within the ± 7 deg. acceptance angle range of the probe, the angular sensitivity bias error in boundary layer pitot measurements is less than $^{+0}_{-0.01} Q_{ref}$ except near separation and reattachment. In those regions, the mean flow inclination angles exceeded the probe acceptance angle and frequent flow reversals added to measurement uncertainty. The angular sensitivity bias error in kielhead measurements is better than $^{+0}_{-0.005} Q_{ref}$ throughout the flowfield because of the large acceptance angle of the aspirated kielhead probe and because the probe was bent when necessary prior to traversing to optimize its alignment with the mean flow direction known beforehand from smoke flow visualization (see figure 4-6).

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D.1.3 Effect of Turbulence on Pitot Readings

The instantaneous total pressure at a point in the flowfield can be expressed as

$$\tilde{P} = p + \frac{1}{2} \rho (\tilde{U}^2 + \tilde{V}^2 + \tilde{W}^2) \quad (D-1)$$

where \tilde{U} , \tilde{V} , and \tilde{W} are the magnitudes of the instantaneous velocities in the axial, transverse, and spanwise directions, respectively. These instantaneous velocities can be assumed to be comprised of a time-mean component plus a sinusoidally oscillating unsteady component

$$\tilde{U} = U + 2u \sin \omega t \quad (D-2a)$$

$$\tilde{V} = V + 2v \sin \omega t \quad (D-2b)$$

$$\tilde{W} = W + 2w \sin \omega t \quad (D-2c)$$

Substituting eqs. (D-2) into eq. (D-1) and time averaging yields

$$P = p + \frac{1}{2} \rho (U^2 + V^2 + W^2 + \overline{u^2} + \overline{v^2} + \overline{w^2}) \quad (D-3)$$

Thus, when a pitot tube is used in a turbulent stream its reading can exceed the total pressure corresponding to the mean flow by an amount proportional to the mean kinetic pressure of the turbulent velocity fluctuations, $1/2 \rho (\overline{u^2} + \overline{v^2} + \overline{w^2})$. Goldstein (ref. 58) suggested that the pitot reading should be corrected by the entire turbulent kinetic pressure. However, the magnitude of any correction should depend on the scale as well as the intensity of the turbulence fluctuations (ref. 59).

In the current study, the turbulence scale is large compared to the diameter of the pitot probes employed. The flow approaches the probe at randomly varying inclination angles due to turbulence fluctuations. Such inclination angles can be quite large for turbulence intensities at which the mean kinetic pressure, ΔP_t , is significant as shown in Table D-1. For example, at a 7.5 percent turbulence level having a mean kinetic pressure of $0.0169 Q_{ref}$, the flow angle occasionally exceeds the ± 30 deg. acceptance of

TABLE D-1. MAXIMUM FLOW ANGLES INDUCED BY TURBULENT FLUCTUATIONS

$$(U = .5 U_{\text{ref}}, V = W = 0, \sqrt{u^2} = \sqrt{v^2} = \sqrt{w^2})$$

$\frac{\sqrt{u^2}}{U_{\text{ref}}}$	$\frac{\Delta P_t}{Q_{\text{ref}}}$	ϕ_{max} (deg)
0	0	0
.025	.0019	± 8.9
.050	.0075	± 19.5
.075	.0169	± 31.2
.100	.030	± 43.3
.125	.047	± 54.7

the aspirated kielhead probes. At such large inclination angles the pitot probe would read low causing the time-averaged pitot reading to exceed the total pressure corresponding to the static pressure and the mean flow by an amount which is less than the mean kinetic pressure of the turbulent velocity fluctuations.

Since a rigorous procedure is not presently available, the total pressure data tabulated in Table IV have not been corrected for the effect of the turbulent kinetic pressure. However, it is the author's opinion that such a correction would be much less than the magnitude of the mean kinetic pressure.

D.1.4 Estimate of Total Pressure Accuracy

The accuracy of the total pressure measurement varied throughout the flowfield. In the freestream and near the test surface (except near separation and reattachment) overall accuracy was better than $\pm 0.01 Q_{\text{ref}}$. In other parts of the flowfield measurements were less accurate but high turbulence levels and flow reversals preclude a quantitative estimate of the error.

D.2 Accuracy of Hot-Film Measurements

In many flow experiments the accuracy of hot-film measurements can be easily quantified and is limited only by the accuracy of the calibration, the linearizer settings, and the sensitivity of the sensor to moderate flow

angularity. In the current study flow reversals, high turbulence levels, and extreme flow angularity combine to limit the accuracy of the hot-film measurements. Each of these factors will be discussed in this section.

D.2.1 Probe Calibration and Linearization

Hot-film probes were calibrated in a 3.8 cm dia low turbulence calibration jet. The probes were aligned such that the sensor was perpendicular to the jet axis and the tips of the needle supports were parallel to the jet axis. Mean velocity and bridge output voltage were recorded for 20 jet speeds ranging from $0.01 Q_{ref}$ to $1.20 Q_{ref}$. The mean response equation for each sensor was assumed to conform to a modified King's law in the following form

$$E^2 = A + B U_{jet}^{0.45} \quad (D-4)$$

where E is the bridge output voltage.

The calibration data was then used to calculate coefficients for a fourth-order polynomial linearizer. Maximum deviation of the calibration data from the linearized fit was 2.5%. To account for hot-film aging and day-to-day tunnel temperature changes, a single point in-place calibration was conducted at the start of each test shift to ensure that a 10 volt linearizer output corresponded to 100 ft/sec (30.48 m/sec). This was accomplished by positioning the probe within the test section at a specific location ($x = 7.6$ cm, $y = 10.2$ cm, $z = 0$) where the streamwise velocity was known to equal $0.9925 U_{ref}$ and adjusting the linearizer span accordingly.

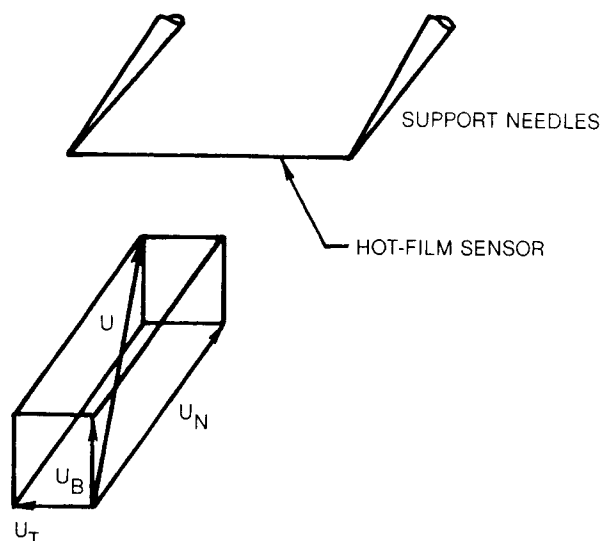
D.2.2 Effect of Turbulence and Flow Angle Variations on Hot-Film Measurements

Jørgensen (ref. 60) has shown that the effective cooling velocity of a hot-film/wire sensor can be expressed as

$$U_{eff}^2 = \tilde{U}_N^2 + h^2 \tilde{U}_B^2 + k^2 \tilde{U}_T^2 \quad (D-5)$$

where \tilde{U}_N , \tilde{U}_B , and \tilde{U}_T are the normal, binormal, and tangential components of the instantaneous velocity vector as shown in the sketch. These velocity components correspond to the instantaneous axial, \tilde{U} , transverse, \tilde{V} , and spanwise, \tilde{W} , velocity components in the test section. Thus, the effective cooling velocity can be written as

$$\tilde{U}_{eff}^2 = \tilde{U}_2 + h^2 \tilde{V}^2 + k^2 \tilde{W}^2 \quad (D-6)$$



The coefficients h and k are functions of the probe geometry and should be determined from calibration. Typical values for h and k are 1.05 and 0.18, respectively (ref. 60). Replacing the instantaneous velocity components in eq. (D-6) with the time-mean and fluctuating velocity components (eqs. D-2) and time averaging yields the following expression for the effective cooling velocity

$$U_{eff} = \sqrt{[(U + u)^2 + h^2 (V + v)^2]}^{1/2} \quad (D-7)$$

assuming k^2 is small and $W \approx 0$. After expanding the rhs of eqs. (D-7) with a binomial expansion and performing the indicated time average, the bias in single-sensor hot-film measurements of axial velocity due to transverse velocity and axial and transverse turbulence can be estimated.

$$\frac{\Delta U_{eff}}{U} = 1 + \frac{h^2 (\overline{v^2 + v'^2})}{2 U^2} \quad (D-8)$$

A comparison of hot-film and LV data acquired at Station 18 ($x = 67.3$ cm) is shown in figure D-1 to indicate the magnitude of this bias error in the present study. Data at Station 18 was chosen for illustration because it is the location of the maximum bias error. Except near the wall, the difference between the hot-film data and U/U_{ref} measured with the LV is approximately 0.1

U_{ref} . The hot-film data also measures approximately $0.05 U_{ref}$ higher than the streamwise velocity component, $\sqrt{U^2 + V^2}/U_{ref}$. However, the U_{eff} profile calculated from LV data using eq. (D-7) approximates the hot-film data, thus verifying the magnitude of the bias error given in eq. (D-8).

D.2.3 Effect of Flow Reversals on Hot-Film Output

Since a single-component hot-film probe cannot distinguish the direction of the effective cooling velocity, the bridge output voltage is always positive, even in regions or periods of reversed flow. This rectification of the velocity signal can cause the measured time-averaged effective cooling velocity to be significantly larger than the streamwise mean velocity and the indicated turbulence level to be lower than actual when flow reversals occur during the averaging period (see Section D.3 below.)

D.3 Comparison of Hot-Film, LV, and Pitot Data Near Separation

LV and hot-film measurements of the mean streamwise velocity and turbulence profiles at Station 11 ($x = 40.6$ cm) near separation are plotted in figure D-2. In addition, the mean streamwise velocity profile calculated from total pressure measurements assuming constant static pressures across the traverse is plotted for comparison. Several aspects of these profiles are interesting.

Near the wall, where the forward flow fraction, γ_{p_U} , is approximately 0.5, the mean velocity measured with the LV approaches zero as y approaches zero. However, the pitot and hot-film data approach a constant positive value. This positive value occurs because the hot-film probe and, to a lesser extent, the pitot probe are directionally insensitive and tend to rectify the velocity fluctuations causing the time-averaged velocity to have a positive bias. Signal rectification also effects the turbulence measurements made with the hot-film in regions of the flow where $\gamma_{p_U} < 1.0$. Near the wall, the turbulence measured with the hot-film is half the LV measurement because the peak-to-peak oscillation sensed by the hot-film are half the actual value because of signal rectification. Near the freestream, where the turbulence levels are low, LV and hot-film mean velocity and turbulence measurements are nearly identical. The mean velocity inferred from pitot readings is significantly lower than actual, however, because of the negative transverse pressure gradient near separation.

DATA OBTAINED AT STATION 18, $x = 67.3$ cm, $z = 0$

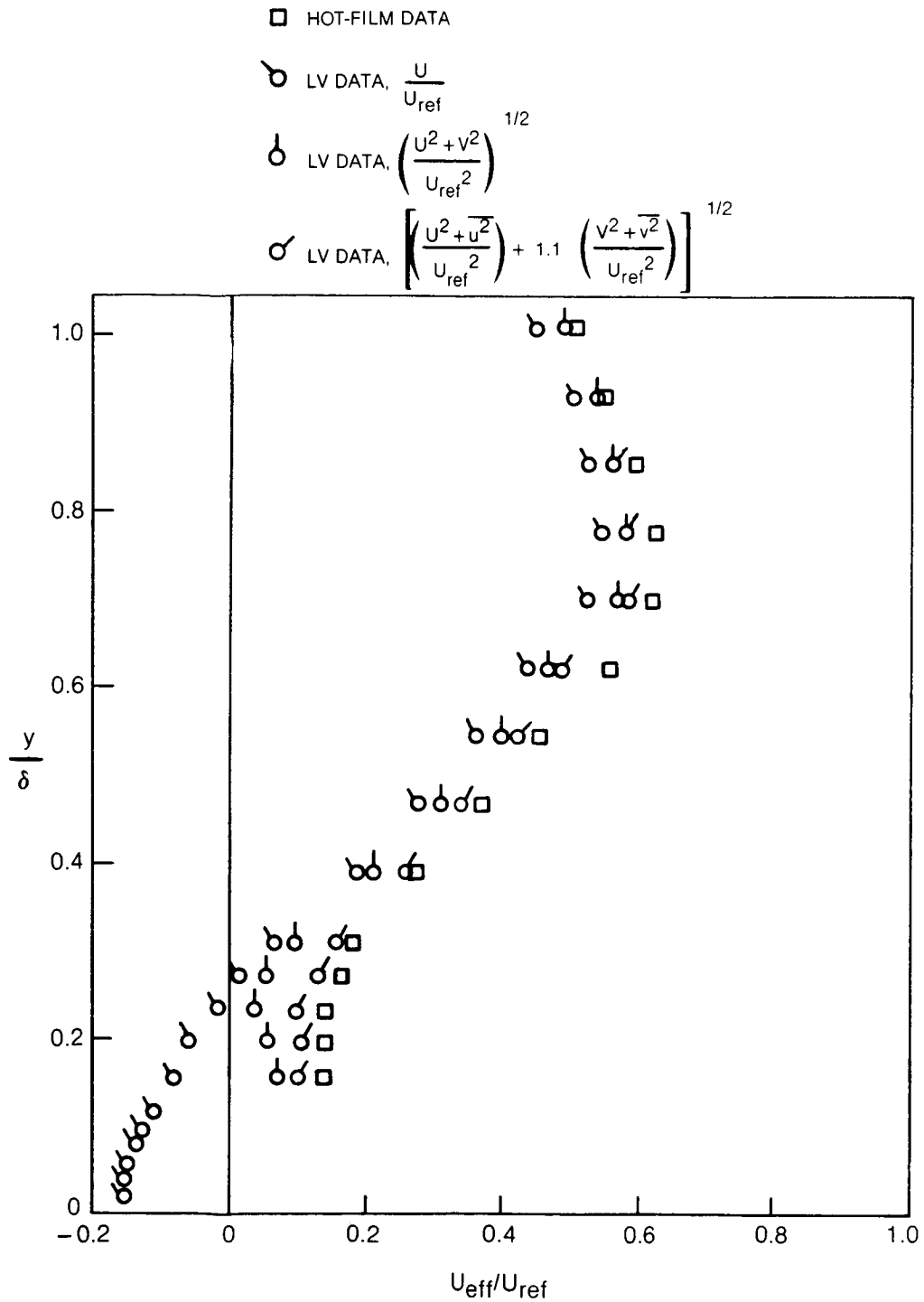


Figure D-1 Comparison of Hot-Film and LV Data

DATA OBTAINED AT STATION 11, $x = 40.6$ cm, $z = 0$

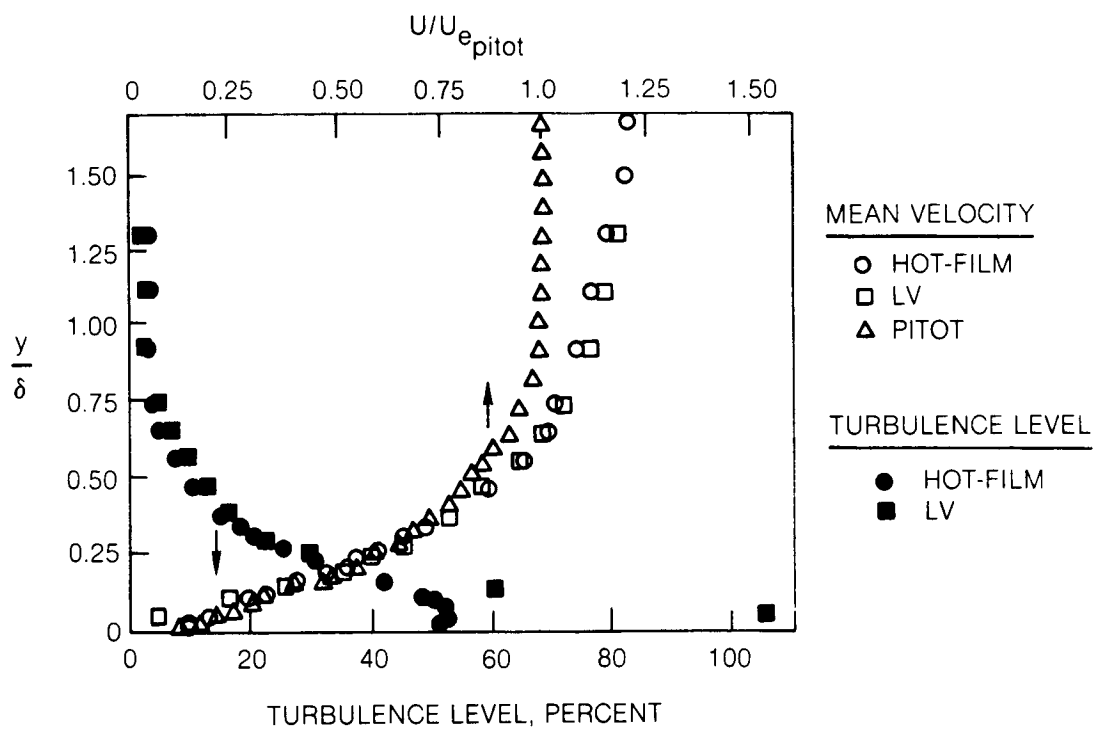


Figure D-2 Comparison of Hot-Film, LV, and Pitot Data Near Separation

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16. Abstract <p>The separation and reattachment of a large-scale, two-dimensional turbulent boundary layer at low subsonic speed on a flat plate has been studied experimentally. The separation bubble was 55 cm long and had a maximum bubble thickness, measured to the height of the mean dividing streamline, of 17 cm, which was twice the thickness of the inlet boundary layer. A combination of laser velocimetry, hot-wire anemometry, pneumatic probing techniques, and flow visualization were used as diagnostics. Principal findings were that an outer inviscid rotational flow was defined which essentially convected over the blockage associated with the inner, viscously dominated bubble recirculation region. A strong backflow region in which the flow moved upstream 100 percent of the time was measured near the test surface over the central 35 percent of the bubble. A laminar backflow boundary layer having pseudo-turbulent characteristics including a log-linear velocity profile was generated under the highly turbulent backflow. Velocity profile shapes in the reversed flow region matched a previously developed universal backflow profile at the upstream edge of the separation region but not in the steady backflow region downstream. A smoke flow visualization movie and hot-film measurements revealed low frequency nonperiodic flapping at reattachment. However, forward flow fraction data at reattachment and mean velocity profiles in the redeveloping boundary layer downstream of reattachment correlated with backward-facing step data when the axial dimension was scaled by the distance from the maximum bubble thickness to reattachment.</p>					
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